ALLIS-CHALMERS

4TH QUARTER 1954

Electrical REVIEW

What to Do When LOADS GROW

Use a Vault-Type Power Unit to Replace 3 or 4 Separate Distribution Transformers On Pole or Platform

New vault-type power unit saves space, is exceptionally easy to install, reduces maintenance.

It combines three or four distribution core and coil assemblies in a single tank. Unit is so compact that it requires less than half the space needed for a conventional bank of three or four distribution transformers. Put it anywhere: the tank is completely welded and the unit can be operated continuously in locations which may become flooded. Find a spot inside — as was done in the installation shown at right — you can locate it in any corner.

Factory Assembly Simplifies Installation

Units consist of either three or four distribution transformer core and coil assemblies to supply three-phase power or three-phase power and single-phase lighting loads. Metering connections are simplified by mounting current transformers in the case. Potential transformers can also be mounted internally if desired. Assemblies are internally connected at the factory and leads are terminated at the cover. There is no primary or secondary bus work to be done at the point of installation. If a three-assembly unit is desired for present needs, room can be left for a fourth assembly to be added at a later date when requirements increase.

A-4499

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Electrical REVIEW

THE COVER

WORLD'S FIRST AND SECOND close-coupled cross-compound reheat steam turbine-generator units are now in operation at Wisconsin Electric Power Company's Oak Creek Station, supplying 240 megawatts of power for homes and industry. Operating on the lowest vacuum of any machines in the world, large 1800-rpm low pressure cylinders take full advantage of steam expansion to ½-inch Hg absolute. Operating since September 1953 and October 1954, these compact, single-foundation units are the first two of three for 1575, 1800, and 2000-psig inlet steam, respectively, with 1000 F initial and 1000 F reheat temperatures.

A-C Staff Photo by M. Durante

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Fully Supercharged Generator...

TEST PERFORMANCE SURPASSES EXPECTATIONS

by **L. T. ROSENBERG**
Engineer-in-Charge AC Design
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and

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Observed temperatures, losses, efficiencies, and characteristics are summarized and compared with those of conventionally cooled machines.

SHOP TESTS on the first fully supercharged generator have established beyond all doubt the complete adequacy of the design and the splendid performance predicted in earlier papers.[1, 2] In many respects, the machine behavior has exceeded calculations. A prototype of 3600-rpm machines that can now be rated 300 megawatts and larger, it embodies many new features permitting full utilization of this new cooling principle.

Temperatures are low

Temperature tests were obtained by loading the generator at zero power factor on a standardized 66-mw unit in parallel with a 40-mva test machine. The initial shop test setup, Figure 1, shows the 66-mw generator with supercharged rotor driven by a dc motor and gear in the left background. A total of fifteen heat runs were completed at 5, 10, 15, 20, 30, 45, 60, and 70 psig hydrogen pressure. In addition to the many internal detector and thermocouple readings, temperatures were also measured on such external parts as terminal bushings, stator shell, brush holders and collector rings. Temperature points were taken at zero power factor at loads equivalent to 0, 47, and 60 mva, and at terminal voltages ranging up to 16,200 volts. From the families of curves through these points the operating temperatures of all parts of the unit can be determined for any load and pressure.

The newly developed single-stage blower yielded 20 percent more pressure than any of the two-stage blowers previously used, with a substantial reduction in power input per cfm. As a result, ventilation was better than expected.

Tests indicated that even at 5 psig the full 47-mva load can be carried without reaching accepted temperature limits on either rotor or stator copper. The embedded resistance detector, placed between coils at the hot end of the machine, showed a rise of 75 C, while the maximum strand rise at the same end measured 81 C at this load. This difference of only 6 C between maximum embedded resistance detector temperature and copper temperature in the same region was virtually constant at all pressures both at 47 and 60 mva. This confirms earlier conclusions[3] that by means of the separate axial cooling ducts in the stator core, Figure 2, the copper and iron can be kept at nearly the same temperature. Stator coil differential expansion is reduced by this factor as well as by the reduced machine length and lower average coil temperature.

The tests show that nearly 80 percent overload at 70 psig is necessary to get the hottest part of the generator copper up to the 130 C limit based on the proposed revisions of the AIEE Standard No. 1 and the ASA Standard C-50. At all pressures and loads, the rotor hot-spot temperature is below that of the stator.

Electrical characteristics also favorable

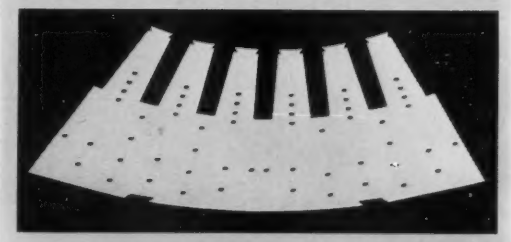
Test saturation and synchronous impedance curves are shown in Figure 3. Among the test results that were more favorable than original calculations are a somewhat reduced saturation at the high flux densities, due to the use of oriented grain core iron, and a correspondingly reduced core loss. The former reduces the field current required

under load, while the latter improves efficiency. As indicated by the curves, the short circuit ratio is 0.83 at the nominal 40-mw rating. This more than meets the requirements of the preferred standard design. Yet the full-load excitation of this machine is only 170 kw, which is a substantial improvement in the originally anticipated excitation requirements of well over 200 kw.

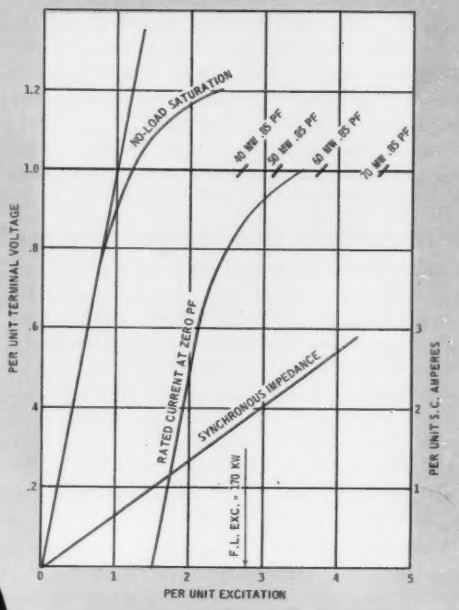
The generator reactances obtained from test are shown in Table I as compared with those of a conventionally cooled 40-mw preferred standard unit.

Of special interest are the relatively high subtransient, negative, and zero sequence reactances that limit mechanical forces during faults as well as the maximum interrupting duty of switchgear. The equivalent saturated synchronous reactance, on the other hand, is substantially lower, thus improving the steady-state stability of the supercharged unit as compared to the conventional machine. Transient stability is decreased somewhat because the transient reactance is higher and the total moment of inertia of the unit is reduced 25 percent. In metropolitan centers this would be no handicap, but for widely separated power stations fault clearing time should be reduced in order to assure the same stability limits under transient conditions as for conventionally cooled machines.

The lower Wk^2 also introduces a requirement of rapid governor action in isolated stations. In case of sudden load dumping, fast governor action is necessary to avoid tripping on overspeed and losing station auxiliaries. Several schemes are available to provide for adequate governor response. The inertia governor has been successfully applied for this purpose. This device responds to rates of acceleration beyond a predetermined value and operates



AXIAL HOLES through the stator core laminations form cooling ducts for hydrogen and assist in keeping adjacent copper and iron at near the same temperature. **(FIGURE 2)**

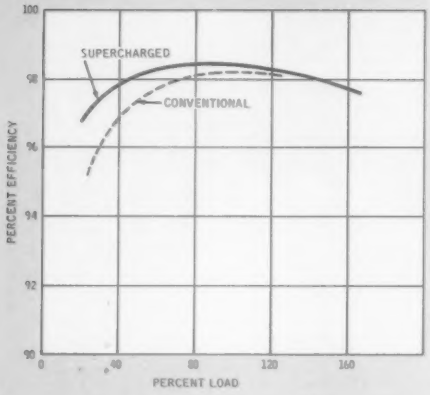


SATURATION and synchronous impedance test curves indicate excitation requirements are less than originally anticipated. **(FIGURE 3)**

ON INITIAL TEST SETUP, the fully supercharged machine was given fifteen heat runs at various hydrogen pressures. **(FIGURE 1)**

TABLE I

	Fully Supercharged	Conventional
Short Circuit Ratio	0.83	0.83
Synchronous Reactance (Unsaturated)	147 %	133 %
Equivalent Reactance (Saturated)	66.7%	80.3%
Subtransient Reactance	15.6%	8.8%
Transient Reactance	25.0%	15.6%
Negative Sequence Reactance	16.0%	9.0%
Zero Sequence Reactance	9.5%	5.3%
Moment of Inertia of Unit	75.0%	100.0%



GREATER EFFICIENCY at all loads than obtained from a comparably rated conventionally cooled generator was indicated. **(FIGURE 4)**

to close the control valves before any appreciable speed change has taken place. Another device consists of separate trip cylinders to partially close the main turbine stop and intercept valves reducing steam flow to that required for boiler auxiliaries. This device would be actuated by either the inertia governor or by auxiliary contacts on the tripping of the generator circuit breaker. Whatever method is used must be adequate not only for loss of full load, but also for the overloads of which the unit is capable.

Low temperatures make efficiency gains possible

The completely supercharged generator was designed and rated to have a full load efficiency equal to that of the conventional machine. Some of its losses are increased, but others are decreased, thus maintaining the same total. Because of the reduced rotor size the friction and surface windage losses are materially lowered. The short length of the core and the long air gap greatly reduce the core losses. Since these savings are all in the fixed losses, the fractional load efficiencies will be higher than those of the conventional machine, provided generator friction is considered in accordance with the ASA Standards.

The increase in rotor I^2R is not as great as might be expected since a portion of the copper duct area replaces the rotor tooth duct of conventional machines, and the magnetic circuit has been redesigned for improved permeance. Moreover, the substantial reduction in mean turn length of both the rotor and the stator conductors helps keep their I^2R losses down. The stator I^2R increase is also limited because the axial stator core cooling increases the available slot area. The increase in the stray load loss is minimized by the short machine length, the long air gap, and by the newly developed flux traps in the end region. In addition, although efficiency computations are based on 75 C copper temperature, a further gain is realized with supercharging because of the low average stator copper temperature when compared with conventional machines of similar hot-spot temperature.

As a result of the superior cooling of this machine, safe temperatures are not exceeded even at low hydrogen pressure. Efficiency at all loads including full load can therefore be further improved by taking advantage of the windage loss associated with lower gas density at lower pressure. Generators of this type, however, will not be rated to operate at maximum permissible temperature. Sufficient gas pressure will be recommended to maintain a safe margin below the allowable temperature. Figure 4 shows the efficiency curve of this machine with gas pressure controlled to provide a hot-spot temperature 10 C below the accepted standard for Class B insulation compared to the efficiency of a conventional 40-mw generator. As indicated, the supercharged generator is more efficient at all loads.

It may be concluded from the tests that pressure can be reduced under normal requirements to get greatest economy, or under sudden or prolonged overloads, pressure can be readily increased to preserve any desired safe temperature margin. Relatively small gas content of the fully supercharged machine makes adding or removing gas quick and inexpensive. The tests indicate that the embedded detector is a reliable guide for pressure adjustments. Complete test data will be published[4] as soon as the more than 6000 temperature and pressure measurements can be evaluated.

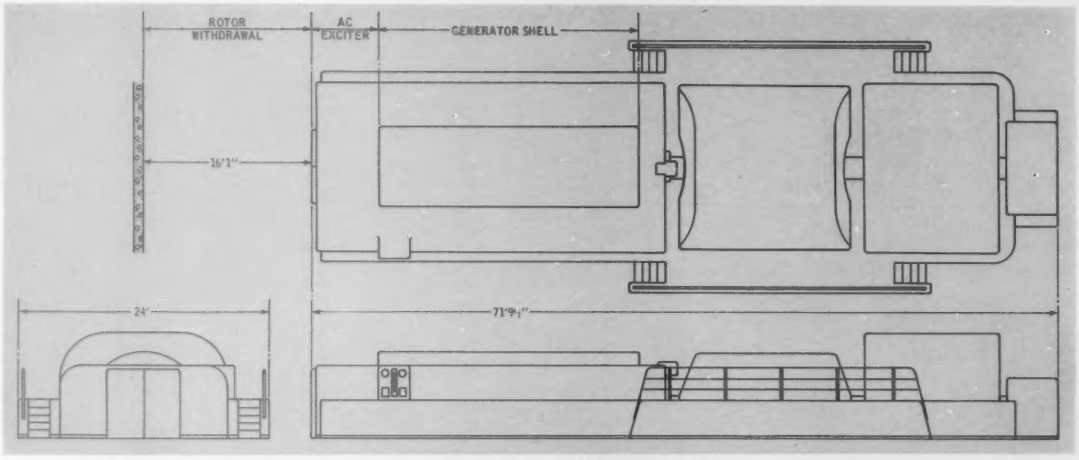
Application to large units

Basic agreement between calculations and tests on the first machine establishes the reliability of present designs for generators with supercharged stators and rotors up to 200 mw at 3600 rpm. Figure 5 shows the outline of the 150-mw unit, rated at 30 psig with an overload of 170.5 mw at 45 psig. The turbine shown has a two-flow exhaust. The generator will have a two-stage blower, each stage similar to the one tested. Four coolers will be used instead of two, each to be twice the length of the coolers in the unit tested. Rotor coil ventilation provides for center discharge.

The hydrogen seals are of the thrust-bearing type with piston areas suitable for any gas pressure up to 100 psig. Shop tests were limited to 70 psig because of limitations in test floor facilities. At 70 psig in either hydrogen or air the sight flow gauges indicated that only a mere trickle of oil was being admitted to the hydrogen side of the seals. The hydrogen leakage was 127 cubic feet per day measured at 70 psig, which is exceptional even when converted to one atmosphere, considering the many temporary pipe connections for manometers and the large number of thermocouples that were brought through gasketed covers for shop test purposes. The seals of all fully supercharged machines will be of similar design, and the units will have overload ratings as high as 60 psig to allow for unexpected system requirements.

One of the great benefits of supercharging is the reduced physical size of both the rotor and stator. The original design calculations, now fully substantiated by shop tests, indicate that the 200-mw fully supercharged generator can be built with a rotor no larger in diameter or length than conventionally cooled rotors built by Allis-Chalmers and now in operation. Tooth root, slot wedge, retaining ring and bore stresses can actually be kept lower because of the large fraction of the rotor copper section that is replaced by gas passages.

The high blower efficiency means that blower losses are not prohibitive for larger machines. Machine efficiencies



SHORT ROTOR withdrawal distance and compactness of the ac exciter are indicated on this drawing of a 150-mw, 3600-rpm unit. **(FIG. 5)**

are competitive, and the use of a single cooling medium circulated by one blower greatly simplifies ventilation. Large fully supercharged generators will require exciters of 750 kw or more. Three types of exciters are available — namely, the geared conventional exciter, the motor-generator set, or the new ac exciter[5] that eliminates commutator, brushes and rotating windings. The compact design of the 3600-rpm ac exciter is indicated in Figure 5.

New cooling principle fulfills important need

Growth in capability of turbine generators had reached the point where physical properties of rotor forgings and retaining rings became a serious limitation. The small rotors of supercharged generators are not only free from these limitations but high quality forgings are more readily obtained because of ease of manufacture, heat treatment, and inspection. Their short length is easily ventilated with blowers of moderate capacity, and power plant space requirements are reduced. Combining with the short length, the lower average temperature and reduced temperature drop from copper to iron afford maximum protection against differential expansion of coils. The supercharged generator will also find wide application in the replacement of obsolete turbine generators in stations where larger capacity is needed but where space is lacking for plant enlargement.

The high reactances cut switchgear costs and reduce electrical and mechanical injury in case of faults, while the higher saturation increases the steady-state stability of the supercharged unit. Its compact, lightweight design saves in crane and foundation costs and reduces maintenance by virtue of its low gas and lubrication requirements. Efficiencies are especially high at fractional loads, thus insuring that the supercharged generator will continue to be an economical machine to operate long after it has ceased to be a base load unit.

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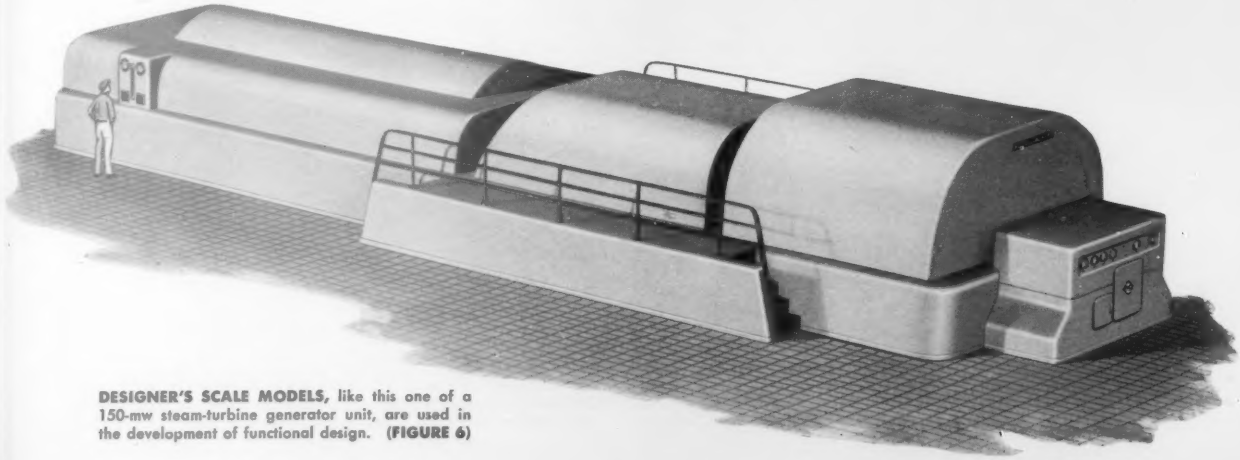
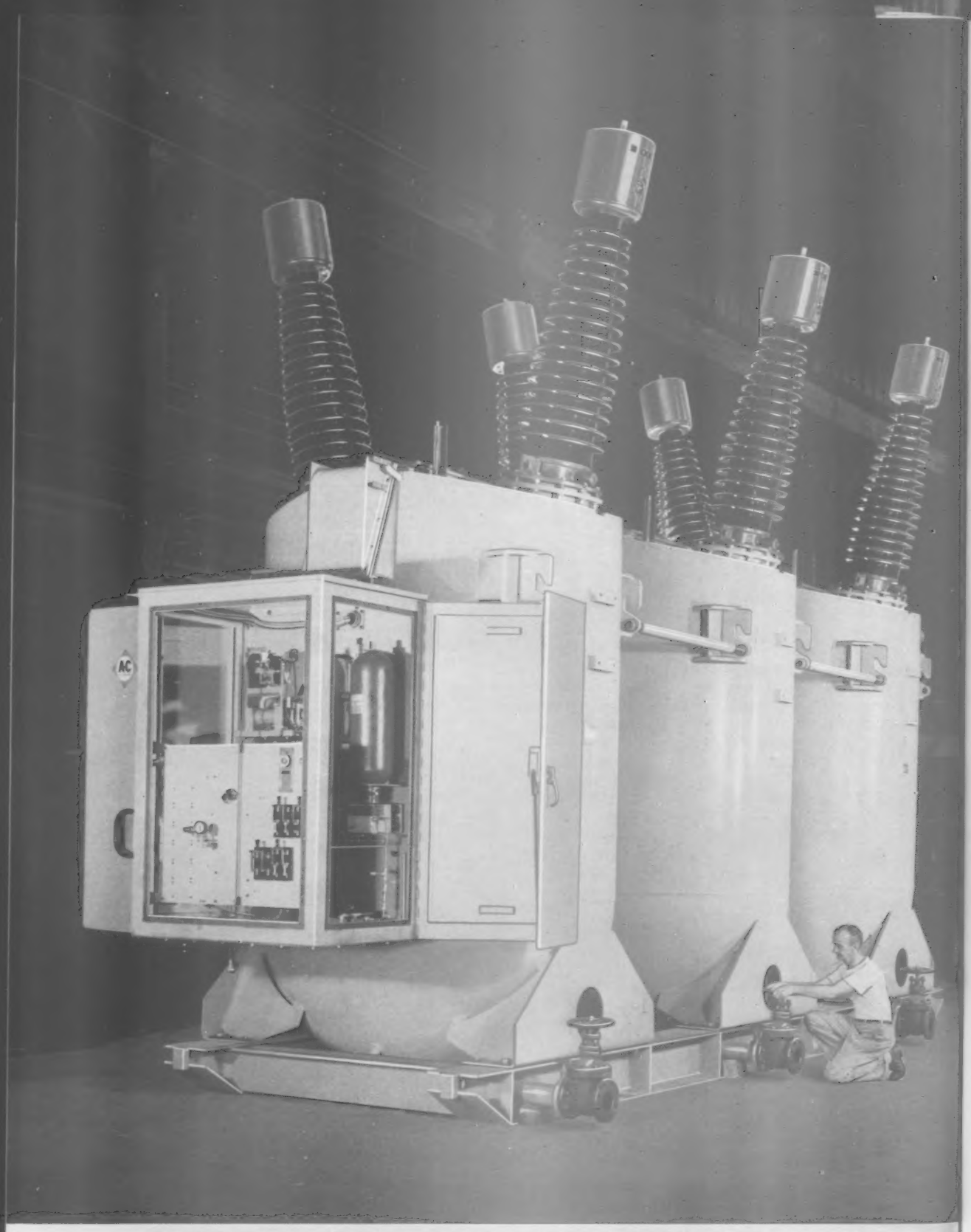


DESIGNER'S SCALE MODELS, like this one of a 150-mw steam-turbine generator unit, are used in the development of functional design. **(FIGURE 6)**



THE LARGEST BREAKER ever equipped with a hydraulic operator stands ready for shipment to a large west coast utility. With new oil- and space-conserving tank design, this unit — the first in a group of 10,000,000-kva, 230-kv breakers — utilizes a three-cycle *Ruptor* interrupting device. The *Pneu-Draulic* operator in cabinet at left can reclose so rapidly that time delay is incorporated to assure full deionization of the conductive air surrounding a fault between repetitive reclosings.

SUBMERGED-ARC FURNACE is used for ferro-alloy smelting.

INDOOR-TYPE furnace transformer, rated 20,000 kva, 23,400-400 volts, is designed for steel melting and refining. **(FIGURE 1)**

New Arc-Furnace Processes

SPOTLIGHT TRANSFORMER DESIGN DETAILS

by **E. G. ASHBAUGH**
Allis-Chalmers Mfg. Co.
Pittsburgh Works

Each of the many types of arc-furnace melting and refining operations requires specific transformer characteristics.

TODAY THE MELTING AND REFINING of steel and iron is only one of many interesting applications of arc furnaces. In fact, it is said that practically any operation that requires a high temperature to promote a chemical or physical change can be carried out in an arc furnace.

Arc furnaces can be divided into three general classes: indirect arc, exposed arc, and submerged arc. The first class is used with small single-phase installations for melting or refining limited quantities of metal. The exposed-arc type is generally used in larger three-phase furnaces for the melting or refining of steel, iron, and nonferrous metals. The submerged-arc type is used for melting nonmetallic materials and for oxide reduction in the production of phosphorus, iron, cobalt, nickel, tin, beryllium, zirconium, and other oxides.

Many uses of the submerged-arc type furnaces are seldom revealed, since they deal with very special processes for particular industries. Among these special processes are the production of calcium carbide; the melting of nonmetals, such as abrasives, cast refractories, glass, slags; and the melting of fused materials, such as silica, alumina, and magnesia.

Special voltages required

Each application of an arc furnace has its own special voltage requirements. Exposed-arc furnace voltages have been increasing in the past few years, and 450 volts on the highest tap is now being used for melting of steel. In submerged-arc furnaces the top voltage may be as high as 150 volts.

Supplying these voltages are a variety of arc-furnace transformers. These transformers vary widely in size and incorporate many features which were developed especially for arc-furnace applications. Basically, furnace transformers have been unchanged in the last 20 years except for design improvements in insulation, gasketing, and tap-changing mechanisms. Most of the improvements were aimed at better efficiency, less weight, extended life, and a reduction in maintenance.

Cooling designed to fit application

Transformers are rated at either 40 or 55 C rise, with the 55 C units being somewhat more popular at this time. The 40 C unit will carry 30 percent more power than a 55 C transformer. While it is true that in many instances the 40 C transformer carries the additional 30 percent overload permissible, it is not recommended that any increase in the overloads over and above this value be used, as rapid deterioration of the insulation will result.

There are a number of methods commonly used to cool furnace transformers. These are classified as:

a. Self-cooled.
b. Self and forced-air cooled.
c. Forced-oil cooled with oil-to-air heat exchangers.
d. Forced-oil cooled with external oil-to-water heat exchangers.
e. Water cooled with internal water-cooling coils.
f. Water cooled with natural circulation of oil through external coolers or heat exchangers.

Since plenty of cooling water is usually available where furnace transformers are installed, water cooling is almost always used. This method of cooling is particularly advantageous for furnace transformers installed indoors or in separate transformer rooms where air conditions limit the effectiveness of self or forced-air cooling.

The construction of internally water-cooled transformers has not changed appreciably since first introduced about 30 years ago. A transformer of this type is shown in Figure 1. The cooling coils are entirely hidden from view.

Thermo-siphon type cooling, as shown in Figure 2, is now available for the larger sizes of power and furnace transformers. This method of cooling resembles forced-oil cooling with oil-to-water heat exchangers except that the oil is not forced through the cooler but flows by gravity. No pumps are required and maintenance is kept to a minimum.

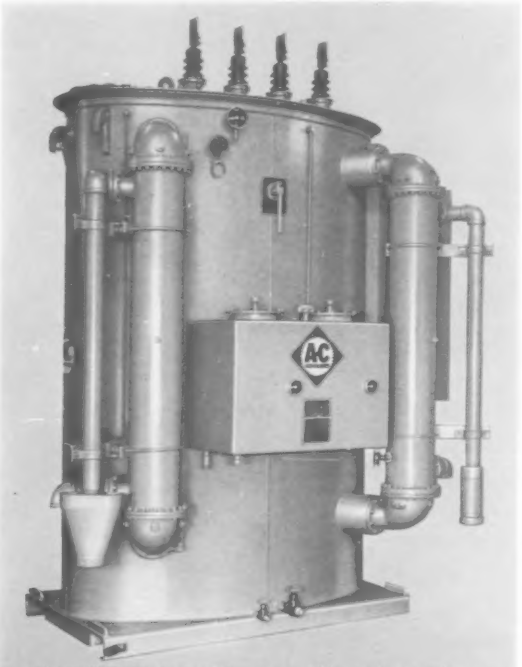
Forced-oil cooling with oil-to-water heat exchangers provides a faster and more effective means of cooling transformers of 15,000 kva and larger but is not an economical method on the smaller transformers. In standard practice, two heat exchangers are used on each transformer. This is done to permit periodic inspection and cleaning of one cooler while carrying loads up to 60 or 75 percent normal. The arrangement also permits carrying reduced kva if one cooler should fail during operation.

Askarel liquid or inhibited oil used

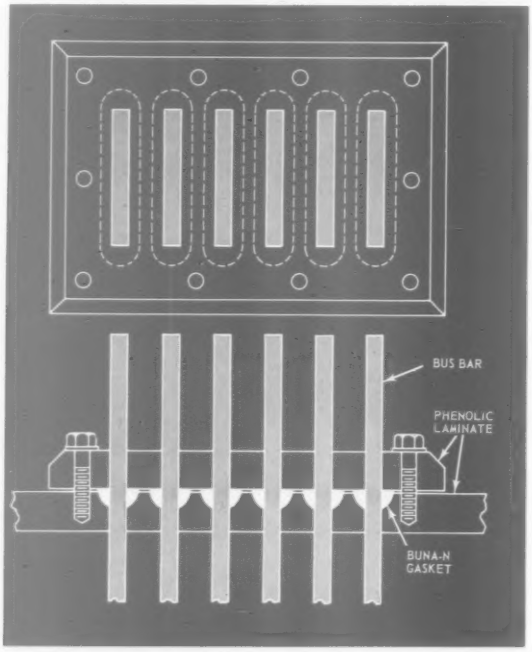
At present, manufacturers recommend the use of inhibited oil for furnace transformers. The inhibited oil provides additional insulation strength, since this oil deteriorates less rapidly when hot and exposed to oxygen-laden air.

Askarel liquid is being specified by users in increasing numbers. Due to the recently developed buna N gasketing material, it is now possible to gasket the secondary bus and make a reasonably tight seal. The buna N gasketing used on a secondary bus is shown in Figure 3.

Since askarel liquid is heavier than water, water condensation will float on the surface of the askarel liquid, making flashovers and transformer failure possible. To

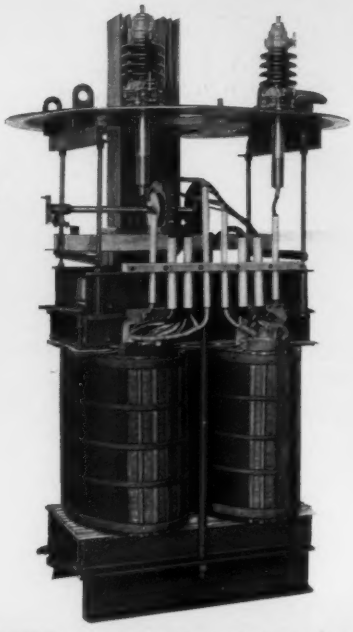


OIL-TO-WATER heat exchanger outside tank operates on thermo-syphon principle on this 10,000-kva transformer. **(FIG. 2)**



BUNA *N* GASKETING tightly seals the secondary bus and permits the use of askarel liquid in furnace transformers. **(FIGURE 3)**

OPTIMUM FURNACE POWER FACTOR is obtained by choosing the proper tap on the reactor at base of transformer. **(FIG. 4)**



EASY ACCESS to the tap-changing mechanism is obtained in this single-phase, 1500-kva, 13,800-75-volt furnace unit. **(FIG. 5)**

eliminate this hazard, insulation boots are placed around the bus bars at liquid level, with the lower end of the boots extending a half inch or more under the oil level.

Gas absorbers can be furnished and are recommended when transformers are located indoors or in confined areas. Used on askarel-filled transformers, gas absorbers neutralize the harmful effects of otherwise highly corrosive and toxic gases that might escape under certain conditions.

Standard designs may include reactors

In many instances, separate reactors with up to 30 percent reactance are considered an important part in the design of the arc-furnace transformer. However, on the submerged-arc transformers it is not necessary to have additional reactance in the circuit. When additional reactance is required, the reactor is normally mounted as shown in Figure 4. The reactor is usually tapped and the percentage reactance changed with the transformer taps to provide ideal total reactance for the process. This type of reactor arrangement makes possible short secondary leads or bus bars, and tends to keep the reactance of the transformer to a minimum.

Tap changers are designed for frequent use

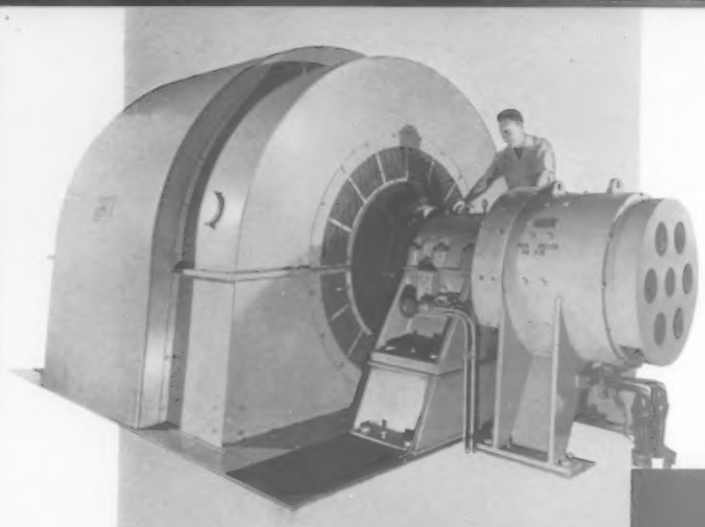
Tap changes are made with the transformer de-energized, thus simplifying the tap-changing mechanism. In most instances, remotely controlled motor-operated tap changers with emergency manual controls are supplied with these units. Furnace transformer tap changers have heavy contacts and large contact surfaces to provide greater contact life with frequent operation, whereas power transformer tap changers have point contact to maintain good contact. The furnace transformer tap changer is kept clean from constant use, while the tap changer on a power transformer may remain in one position for long periods, making it necessary to maintain high point pressure to insure positive contact.

Furnace transformer tap-changing mechanisms are always arranged for easy inspection and maintenance. It is not necessary to untank the transformer or even remove the main transformer cover to make repairs. Figure 5 shows a small single-phase submerged-arc furnace transformer. Access to this tap changer is obtained through a manhole in the cover.

The large arc-furnace transformer in Figure 1 has a separate tap-changer compartment mounted outside the transformer case. This arrangement is generally preferred for larger units and will undoubtedly become increasingly popular.

Furnace and power units compared

Due to the many special requirements that furnace transformers are designed to meet, their weight in copper and iron is more than double that of a comparable power transformer, but it is not anticipated that furnace-type transformers in new applications will be any larger, weigh more, or add any new problems.



SYNCHRONOUS CONDENSER for arc-furnace load correction at southern steel plant is rated 25,000 kva, 13,800 volts. The direct-connected exciter is rated 150 kw.

SYNCHRONOUS CONDENSER at Arc-Furnace Load

Steadies Power Demands

by **STANLEY E. McDOWELL**
Switchgear Department
Allis-Chalmers Mfg. Co.

A synchronous condenser solves voltage problem created by an arc-furnace load added near the end of a long power line.

THE THREE AMMETERS on the control panel of a large three-phase arc furnace will show at a glance why arc-furnace loads may create voltage problems. Generally, system voltages are not a problem when the furnace is located near a larger power source. Under these conditions furnace load surges are small compared to the source capacity, and line drops are at a minimum. However, when furnace loads are carried over long power lines, voltage disturbances caused by these loads may seriously affect other users on the system.

While modern high speed control of electrode position tends to minimize load swings and shorten the duration of short circuits, the risk of electrode breakage and other mechanical problems prevent faster correction.

Typical heat shows load problem

On large steel or iron melting and refining furnaces, three automatically controlled electrodes are mounted in the furnace roof and are individually raised or lowered by a winch or hydraulic pump. Figure 1 shows a typical arc furnace. To start a heat, the electrode motor control switches on the control panel are turned to automatic, and the electrodes move rapidly downward and touch the scrap. This action forms either a single-phase or three-phase short circuit, and the electrodes automatically reverse to form arcs between the electrodes and the scrap. The scrap, being grounded on the furnace frame, forms a grounded neutral for the arcs.

Since the furnace is loosely filled with a mixture of scrap steel, iron, and possibly some iron ore, a large volume of air spaces are formed throughout the furnace. As the scrap begins to melt around the electrodes, the molten charge flows downward to fill in the air spaces. Because the electrode must be kept a certain distance from the charge in order to maintain an arc, the electrode positioning equipment automatically lowers the electrodes as the metal melts. Thus the electrodes tend to bore into the charge. When enough of the charge becomes molten, the unmelted scrap collapses. This cave-in, as it is commonly termed, often grounds one or more electrodes.

On some furnaces as long as a minute may be required to withdraw the electrodes, and the furnace circuit must be able to withstand these short circuits until the arc is re-established. The severe load swings of the melting period may last from a half hour on small furnaces to several hours on extremely large furnaces. Usually, rather smooth operation is expected during the refining period, except when additions are thrown in the furnace to improve the chemical analysis. During this short period the arc current is again rather rough.

Voltage regulators can't keep up

Feeder voltage regulators are designed to correct changes in line voltage conditions resulting from gradual load changes from no load, or about 10 percent load, to full load over a period of hours or even minutes. The inherent nature of arc furnaces, however, is to change from no load to perhaps three times full load in a matter of a few cycles. Feeder voltage regulators are too slow under these conditions. Two solutions have been applied: static capacitors and synchronous condensers.

Since the capacitance of static capacitors is fixed, means must be provided for switching various portions of the capacitor bank in and out of the circuit when transformer voltage tap positions are changed. Since an arc is a good source of harmonics and since capacitors by their nature tend to emphasize these harmonics, telephone interference may result. Hence, switched capacitors may add to the problem rather than correct it.

Synchronous condenser fills a need

One southern steel company found a need for a synchronous condenser. The equipment utilized in this installation is connected as shown in the single-line diagram, Figure 2. A photograph of the outdoor equipment is shown in Figure 3.

The main power transformer, *A* in Figure 2, has provisions for the future addition of fans to give a forced air-cooled rating of 40,000 kva. A reduced-voltage tap is provided in the low voltage winding for the purpose of starting the synchronous condenser.

Switching and protection of the 13.8-kv apparatus is provided by the outdoor metal-clad switchgear shown at the left in Figure 3. Power is supplied to the switchgear from the main power transformer by means of tubular conductors entering through the switchgear roof bushings of Unit 2. The conductor from the starting tap of the main transformer low voltage winding enters Unit 3 through roof bushings. Unit 4 houses a circuit breaker providing back-up protection for the furnace load. The necessary current and potential transformers are mounted within the switchgear units.

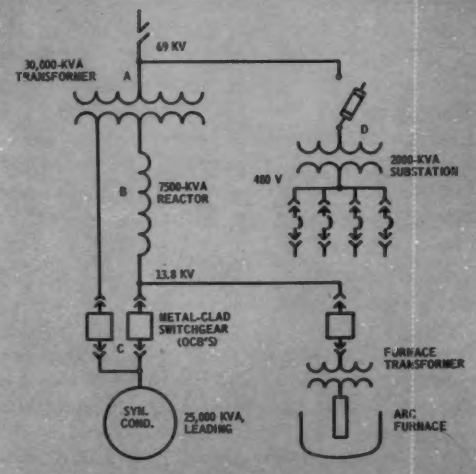
The circuit breakers in the switchgear are operated from an indoor duplex-type control board. This board is shown in Figure 4. Mounted on the front panels of the control board are the required control switches and indicating lights, as well as instruments for indicating and recording conditions existing in the synchronous condenser and feeder units. The relays mounted on the interior panels are required for starting the synchronous condenser, applying the field and transferring it to its running connection.

The control board also contains the control panel for a remotely mounted *Regulex* rotating control which is used to control the excitation of the synchronous condenser.

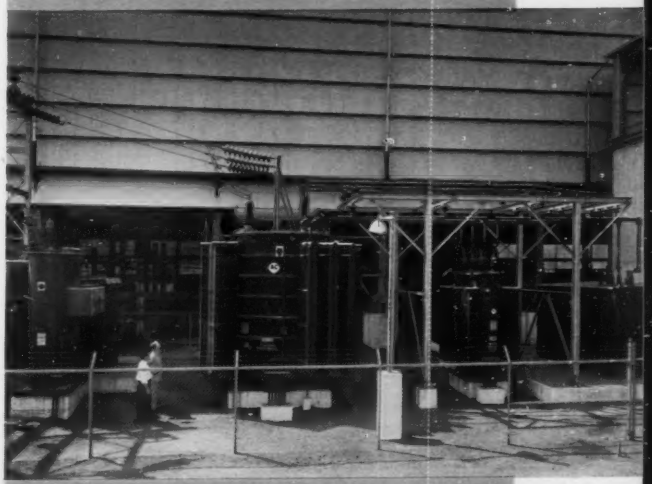
Another item of interest in Figure 3 is the 2000-kva outdoor load center substation, consisting of an oil-filled transformer (left) to step the voltage down from 69 kv to 460 volts, and a group of outdoor 460-volt switchgear which supplies power to the plant auxiliaries, such as lighting equipment and miscellaneous small motors.

An oil-filled, iron-core, series buffer reactor is also shown in Figure 3. This reactor is provided with 25, 20, 15, and 7½ percent reactance taps. The proper tap for maximum damping effect is selected by trial and error to allow the condenser to absorb the maximum amount of kvar. Once the proper setting is obtained, no further change is made unless an additional furnace load is connected.

ELECTRODE POSITION of this four-ton furnace is controlled automatically from the operator panel. **(FIGURE 1)**



REACTOR aids synchronous condenser in limiting effect of arc-furnace load surges on the system voltage. **(FIGURE 2)**



OUTDOOR-TYPE transformers and switchgear serve both the arc furnace and the synchronous condenser. **(FIGURE 3)**

DUPLEX CONTROL BOARD for 13,800-volt synchronous condenser provides protective relaying, metering, and remote breaker operation. The field application equipment and condenser-starting equipment are mounted inside the enclosure. **(FIGURE 4)**

The purpose of the reactor is to offer opposition to the sudden changes which occur when the furnace load is alternately applied and dropped, thus forcing the synchronous condenser to absorb the greater portion of fluctuating component by permitting greater voltage fluctuations on the condenser.

The picture on page 12 shows the synchronous condenser in this installation. It is an indoor air-cooled machine rated 25,000 kva leading and 12,500 kva lagging at 13,800 volts, 720 rpm and requires a 150-kw, direct-connected 125-volt exciter. The machine is of special low reactance design to provide a guaranteed unsaturated transient reactance of 31 percent on a 25,000-kva base. The low reactance requirement results in a machine of slightly greater physical size than normal for the kva rating.

In this application the synchronous condenser supplies the reactive kva required when furnace surges occur, thus reducing the amount of reactive kva which would be supplied by the power company. As a result, the overall stability of the power system is maintained and voltage problems are minimized.

Power factor is controlled

The synchronous condenser can be used to maintain furnace circuit power factor at a value high enough to eliminate penalties incurred by operators of low power factor systems. This advantage may be considered a "by-product" of its use as a voltage regulating device, since the action of the synchronous condenser as a "voltage regulator" maintains a reasonably good power factor. Ideally, the arc furnace itself is operated at 80 to 85 percent power factor. This power factor produces the most efficient overall operation of a furnace.

Figure 5 illustrates how a synchronous condenser is connected to improve power factor.

Figure 6* shows the improved regulation obtained when a synchronous condenser and series buffer reactor are used in an arc-furnace circuit.

The beginning of each chart illustrates system conditions prior to the installation of the condenser, and the remainder of each chart illustrates the improved conditions. It should be pointed out that these charts do not show sudden changes in load or voltage.

In the hypothetical system of Figure 5 the kva is assumed to remain constant at 5000 kva; and Figure 7 shows that by improving the power factor of this system from 0.6, triangle *ABC*, to 0.8, triangle *ADE*, more kw is obtained to perform useful work. Line *EF* represents the leading kvar supplied by the synchronous condenser. Figure 7 also illustrates that it is necessary to supply only 3750 kva at 0.8 power factor to obtain the same 3000-kw load obtained from 5000 kva at 0.6 power factor. In this case the synchronous condenser must supply leading kvar represented by line *CF*.

The ability of a synchronous condenser to supply the reactive kva at a rate sufficiently fast to suit the electric arc-furnace operating characteristics is dependent upon the transient reactance of the machine. A condenser having a relatively low transient reactance will furnish more kilovars during an instantaneous voltage surge than a machine of higher transient reactance, even though both machines may have identical nameplate ratings.

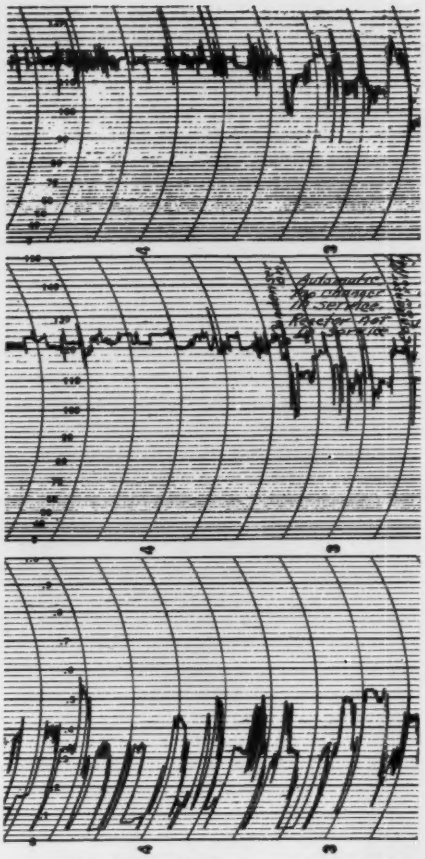
* Charts used through courtesy of T. G. LeClair — from his paper entitled "Arc-Furnace Loads on Long Transmission Lines."

The determination of proper condenser reactance for a given installation can best be determined by a calculating board study of the particular installation and of the power system which serves it. Since the reactance of the furnace transformer and its leads does not usually vary to a great extent for a given furnace size, the principal variables will be the reactances of the synchronous condenser and buffer reactor. These reactances must be selected to suit each individual installation.

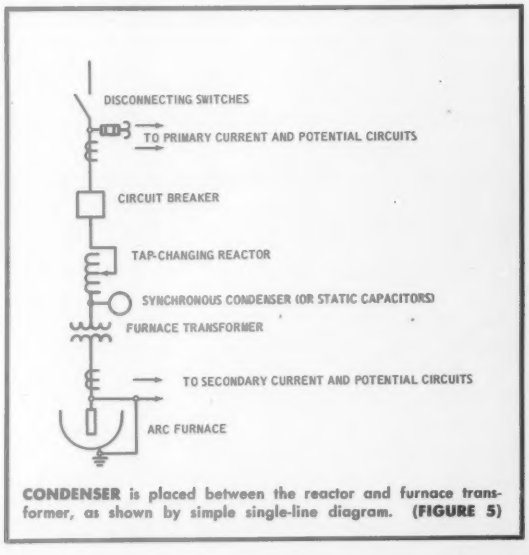
For normal condensers of an equivalent kva rating, a hydrogen-cooled machine will have a transient reactance approximately 20 percent higher than that of an air-cooled machine. This is primarily due to the fact that the more efficient cooling obtained with hydrogen permits the use of a physically smaller machine with correspondingly higher reactances.

Since the low reactance requirements of a synchronous condenser for arc-furnace service require a more expensive modification of design for the hydrogen-cooled machine, and since the hydrogen-cooled machine is greater in initial cost than the air-cooled unit of identical leading kva and reactance, the air-cooled synchronous condenser will be more economical for small and intermediate-size installations. On large installations, however, the lower losses obtained by hydrogen cooling overcome other disadvantages, making the hydrogen-cooled condenser more economical.

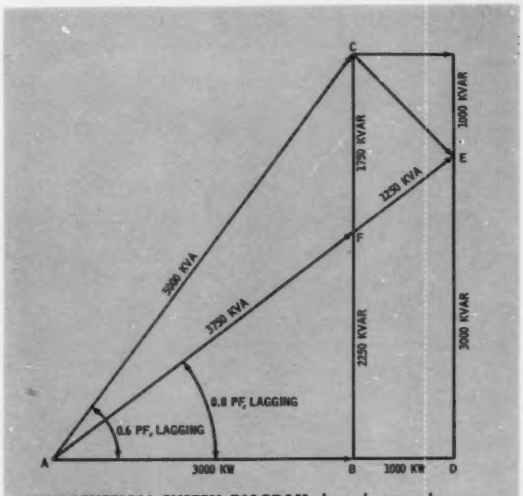
In order to re-establish an arc, the electrodes must be lowered into the charge, resulting in a repeated short circuit. Alternately applying and dropping large portions of furnace load calls for large fluctuations in reactive kva. The synchronous condenser together with the buffer reactor combine to supply the reactive kva demanded by the furnace surges, removing a considerable portion of kilovar transients from the power system. This results in a stable power system which can supply "flicker-free" power to its customers and also furnish the large blocks of power to the furnace user.



SIMULTANEOUS CHARTS show condenser benefit. Condenser with 20 percent reactor was placed in circuit at 3:25. Top chart times 120 is 13.8-kv bus voltage. Center chart times 120 is secondary voltage. Bottom chart times 39,000 is kw demand on system. **(FIG. 6)**



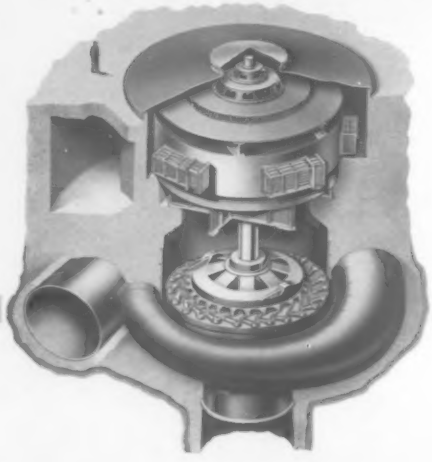
CONDENSER is placed between the reactor and furnace transformer, as shown by simple single-line diagram. **(FIGURE 5)**



HYPOTHETICAL SYSTEM DIAGRAM shows how synchronous condenser can be used to supply reactive power. **(FIGURE 7)**

PUMP-TURBINES

1954 Progress Report



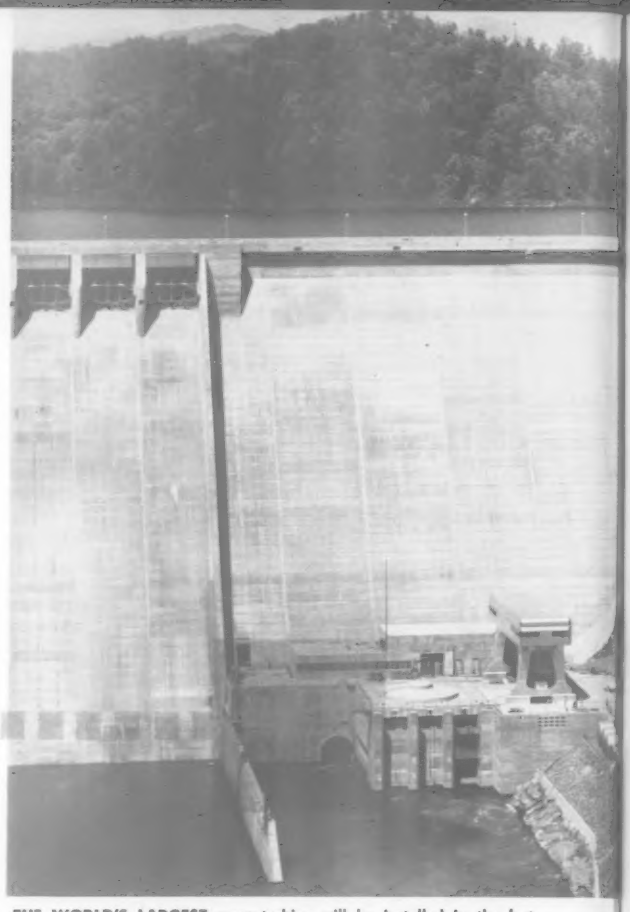
by **FRANK E. JASKI**
Assistant Chief Engineer
Hydraulics Section
Allis-Chalmers Mfg. Co.

Providing both off-peak load and peak-load power, pump-turbines are an economical way to smooth system load curves.

LEVELING PEAKS AND VALLEYS in system load curves has become a major problem in long range power planning. One solution is to store energy when power demands are low for use when power demands are high. This storing of energy is being accomplished with reversible pump-turbines.

A reversible pump-turbine is similar in appearance to a Francis-type hydraulic turbine and, like a turbine, is designed to generate power when revolving in one direction. In addition, it pumps water when driven in the opposite direction by its generator-motor.

System load curves are leveled by using the pump-turbine during off-peak periods, when low-cost surplus power is available, to pump water from a reservoir or supply at one elevation to a storage reservoir at a higher elevation. This stored water is later returned through the unit and drives it as a turbine to generate power during peak demand periods.



THE WORLD'S LARGEST pump-turbine will be installed in the last open bay of the Tennessee Valley Authority's system during 1955. The unit and its location at Hiwassee Dam are indicated.

Can be economical with thermal systems

At first glance, pumping water which consumes power in order to generate power at another time appears impractical. However, closer examination often proves that pumped-storage power, in effect a hydraulic storage battery which converts surplus electrical energy to water power for reconversion when it is needed, can be an economical method of supplying peaking power for both thermal and hydraulic systems.

Today, most of our electrical power is obtained from thermo-electrical systems. Larger and larger steam turbo-generators are coming into use. Higher temperatures and higher pressures are constantly being applied in order to improve performance and increase the ratings of these units. On many systems, operating these units at continuously high load factor is becoming a problem, because in the average load curve there are peaks and valleys that vary during a weekly cycle, and seasonal load demands which change from month to month.

On many systems, some of the steam units necessary to supply the load during working hours of the day must be shut down or put on standby at night or over weekends. After cooling during shutdown, the steam units have to be warmed up again before they can go back on load. Such

alternate heating and cooling can cause serious stress conditions in the units and result in outages for maintenance. If these units can be used to store their energy during low demand periods, rather than being shut down, they can be operated more economically, maintenance can be reduced, and the life of the units materially increased. Pumped-storage hydroelectric power supplies a means of storing this energy.

By supplying the off-peak load which fills the valleys in the load cycle, and supplying the additional energy required during heavy peak loads, pumped storage conserves energy. It supplies the power for the top of the peaks and saves the equivalent amount of capacity load which would have to be supplied by additional steam or other units.

Has advantages in hydro systems

Pumped storage can also utilize surplus hydroelectric power. During rainy seasons or spring thaws, rather than spilling surplus water, much of it can be pumped into storage reservoirs during off-peak periods and released to supply much needed energy when demands are at their peak. Surplus hydraulic energy in a wet season can be pumped into storage for release to replenish diminishing hydraulic power during dry seasons.

Niagara Falls is an excellent example of how surplus hydraulic energy can be utilized by pumped storage. Under the new treaty between Canada and the United States, during the tourist season from May to October it will be necessary to leave a minimum flow over the Falls of 100,000 cfs during the daylight hours. At night this can be reduced to 50,000 cfs. The additional 50,000 cfs of water thus made available is of little use for power at nighttime, but if it can be stored it can be used during the daylight hours to generate much-needed peak-load power. To accomplish this, reversible pump-turbines will be installed in Ontario on the Canadian side, and at Lewiston, New York, on the American side.

These pump-turbines will lift water from the forebays of the new 300-foot head hydraulic plants that are to be added on each side, up into storage reservoirs about 100 feet higher. During the daytime, water will be released under about 90 feet head to generate power through the pump-turbines. This same water can then be used to generate power through additional units in the 300-foot head plants. About 500,000-kw additional capacity can be added to each 300-foot head plant by utilizing pumped storage.

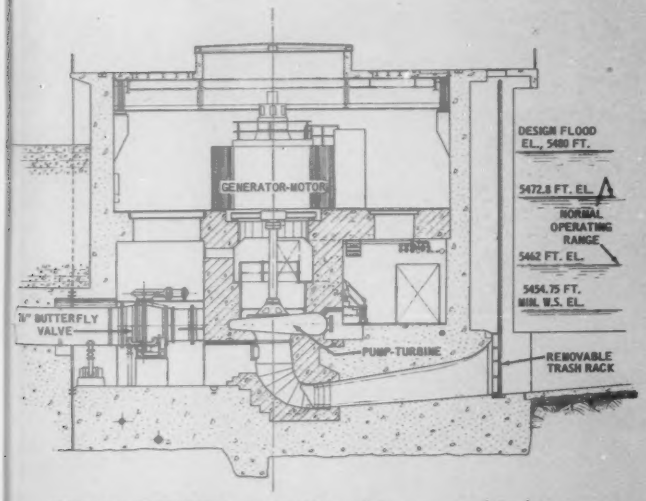
A large reversible pump-turbine will soon be installed at the Hiwassee Power Plant of the Tennessee Valley Authority system. This unit will be the largest reversible pump-turbine in the world, and its motor, rated 102,000 hp, will be the largest motor in the world. At present, there is a conventional Francis turbine in the plant. Because of the seasonal flow in this area, a reversible pump-turbine was determined to be more economical than a duplicate Francis turbine. The reversible pump-turbine and the Francis turbine will develop more energy at less cost per kilowatt than could two conventional Francis turbines (see *Electrical World,* May 11, 1953).

Appearance similar to popular Francis type

With its impeller-runner shaft-connected to the generator-motor, a spiral case to lead the water into the runner for generating power or directing it into the penstock when pumping, a reversible pump-turbine looks like a conventional Francis turbine. The draft tube for discharging water into the tailrace when generating power doubles as a suction tube for pumping the water from the tailrace and guiding it into the impeller-runner.

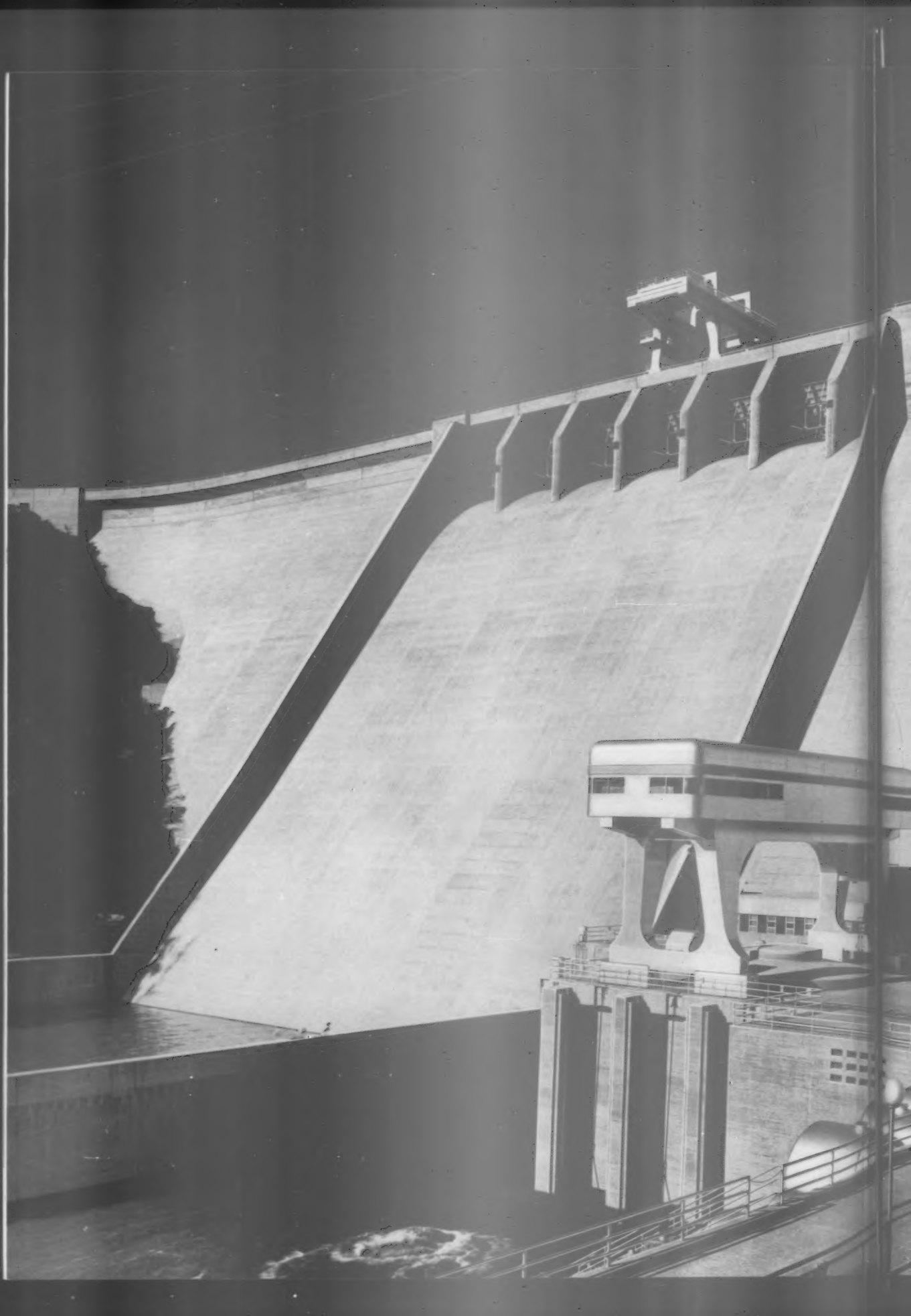
A reversible pump-turbine may have movable wicket gates around the impeller-runner to control the flow of the water in either direction, or the wicket gates can be omitted. Units having wicket gates give a higher efficiency when pumping because, as the storage reservoir is filling, the head will increase and the quantity of water pumped decrease. As the quantity changes, the wicket gates can be adjusted to provide the proper flow for best efficiency. When generating power, wicket gates are used for starting and synchronizing the unit and are then opened wide to develop the maximum power.

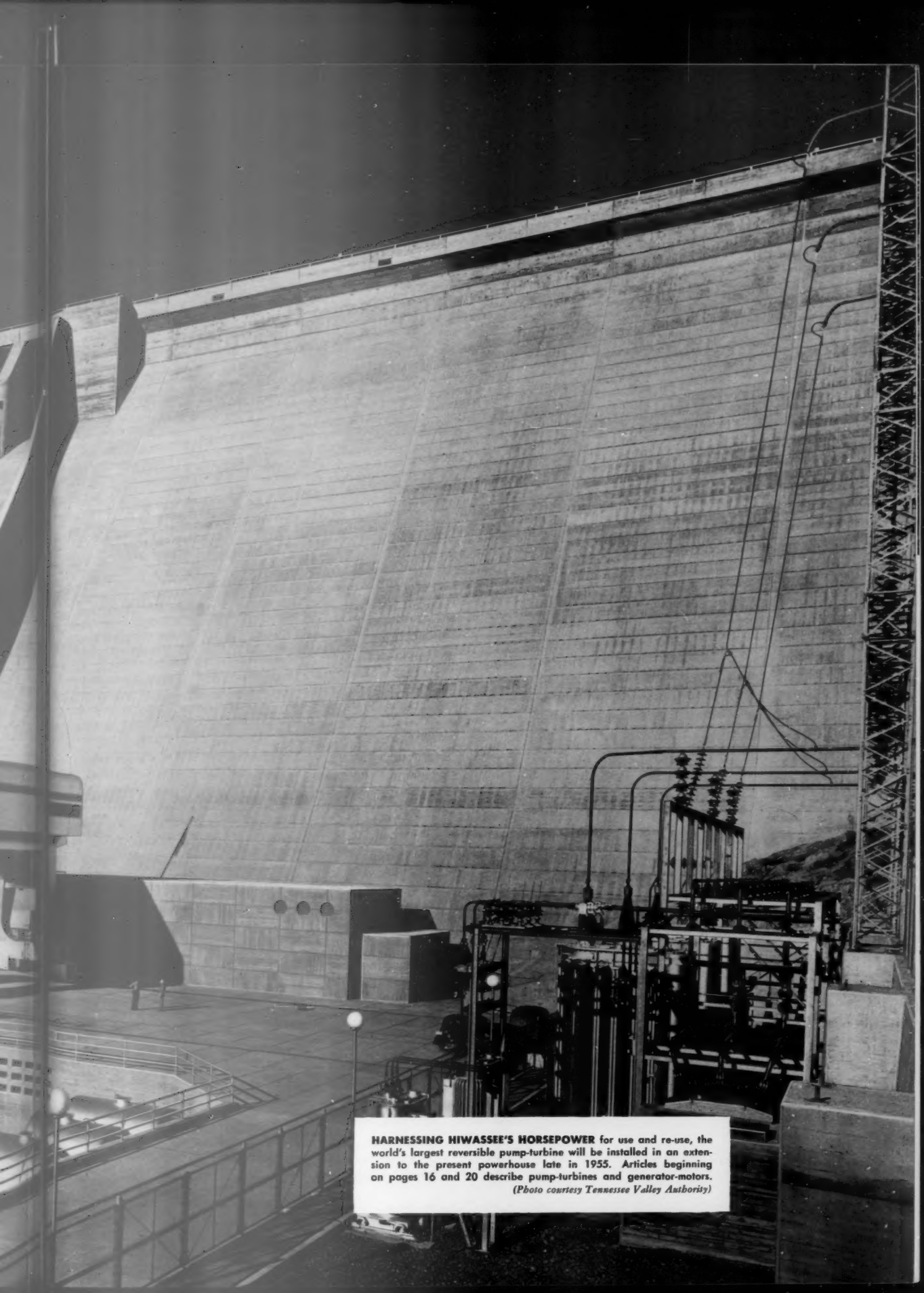
(Continued on page 24)



NOW IN OPERATION, the 12,000-hp Flatiron pump-turbine has a 76-inch butterfly valve to control the flow of water. **(FIGURE 1)**

LOCATED at the extreme left within the Bureau of Reclamation's Flatiron Power and Pumping Plant, the pump-turbine will pump tail-race water through an 8-foot penstock and pressure tunnel system 1.1 miles long to Carter Lake (off picture to left). **(FIGURE 2)**
(Photo courtesy Bureau of Reclamation)





HARNESSING HIWASSEE'S HORSEPOWER for use and re-use, the world's largest reversible pump-turbine will be installed in an extension to the present powerhouse late in 1955. Articles beginning on pages 16 and 20 describe pump-turbines and generator-motors.
(Photo courtesy Tennessee Valley Authority)

GENERATOR-MOTOR UNITS

for Reversible Pump-Turbines

by **H. H. ROTH**
Motor and Generator Section
Allis-Chalmers Mfg. Co.

INSIDE THE FLATIRON Power and Pumping Plant, this 13,000-hp, 8500-kva two-speed reversible generator-motor now in operation is similar in appearance to a conventional hydraulic generator.

Two electrical ratings and modifications to facilitate starting characterize reversible generator-motors.

THE ELECTRICAL HALF of a reversible pumped-storage unit differs from a normal hydro-generator in several respects. The important differences are:

1. It must have a rating both as a motor and as a generator. These ratings are usually different both in kva and power factor, and may sometimes be different in rpm or voltage.
2. It must be capable of starting the unit when operating as a synchronous motor, without excessive system disturbance.
3. It must be able to operate in either direction of rotation.

Ratings depend on hydraulic characteristics

In many cases the amount of power drawn from the system during the pumping cycle will differ considerably from the amount that it is capable of generating. This difference is dependent on the hydraulic characteristics of the particular installation. For example, a unit might require an average of 60,000 hp during the pumping cycle, but might develop only 50,000 hp at full gate during the generating cycle. The electrical unit must be capable of carrying either load without overheating. For this particular example, the motor rating in kva corresponding to 60,000 hp would be:

$$\frac{\text{Hp} \times .746}{\text{Motor Eff.} \times \text{PF}} = \frac{60{,}000 \times .746}{.96 \times 1.00} = 46{,}630 \text{ kva}$$

The output when generating would be:

$$\frac{\text{Hp} \times .746 \times \text{Gen. Eff.}}{\text{PF}} = \frac{50{,}000 \times .746 \times .96}{.90} = 39{,}800 \text{ kva}$$

In the above calculation the assumption has been made that a PF of 100 percent would be satisfactory for synchronous motor operation during the pumping cycle and that 90 percent PF would be required when generating. On this basis the kva motor rating of the unit is 13.7 percent larger than its generator rating.

For single-speed operation the most economical unit is generally one in which the motor and generator ratings are of equal kva. It might be that additional reactive kva capacity would be of benefit during the generating cycle to relieve other units on the system. If this is the case, the unit can be given a generator rating of 80 percent PF, resulting in a generator output of 44,750 kva — nearly the equivalent of the motor rating.

There are a number of other variable conditions which may affect the selection of suitable kva ratings, such as:

1. *If the upper storage reservoir is relatively small,* the pumping head may vary considerably during the daily pumping cycle, with a resulting horsepower variation during each cycle. The greatest power input when pumping would probably occur when the reservoir was empty, and a rating should be selected to suit this condition.
2. *If both upper and lower storage reservoirs are of large capacity,* the hourly fluctuation in power input when pumping would be negligible. The head variation in such an installation would be of a seasonal rather than a daily or hourly variation.
3. *When the head variations are of a seasonal nature* the lower head condition, which requires the greater horsepower for pumping, may occur during the winter months when the water for the air coolers is at its lowest temperatures. This would result in a lower ambient temperature during the period of greatest load, and a kva rating could be selected on the basis of some overload under these conditions.

Since the load characteristics of pumped-storage units vary considerably from one installation to another, each application must be considered in detail on its own merits when selecting the ratings for the electrical unit.

Two-speed units have their place

There are instances where the head variation for a particular installation will make two-speed operation attractive. For example, in the case of large seasonal head variations, turbine efficiency and output will usually be considerably lower under low head conditions than for normal head operation. If, however, the rpm of the unit can be dropped to a speed giving best hydraulic performance for the lower head, overall efficiency will be appreciably improved. This improvement may be sufficient to justify the increased cost of a two-speed unit.

Two-speed operation of synchronous machines may be obtained, within certain limits, by utilizing a single reconnectable rotor winding and two separate stator windings which utilize the same stator slots. For example, one winding could be designed for 24-pole, 300-rpm operation, and the other for 28-pole, 257-rpm operation. The rotor would have 24 salient poles uniformly spaced.

This method of obtaining two-speed operation of synchronous machines is diagrammed in Figures 1 and 2. The upper half of Figure 1 shows the arrangement for 24-pole, 300-rpm operation, and the upper half of Figure 2 shows the 28-pole, 257-rpm arrangement. For simplicity, only one-fourth of the rotor and stator windings are shown. The stator windings are shown for only one phase, each coil shown representing a coil group.

For the 24-pole connection, the machine operates as an ordinary 24-pole unit, having 24 salient poles and a stator winding normal for a 24-pole machine.

For 28-pole operation the rotor field coils are reconnected. The 24 physical poles are divided into groups of six poles per group, and the polarity of all poles in the second and fourth groups are reversed. Connections are brought out from the rotor winding to five collector rings to permit this regrouping which may be accomplished with an external double-throw switch.

The stator winding used for 28-pole operation is normal for a 28-pole machine, with coil groups symmetrically spaced in the stator slots.

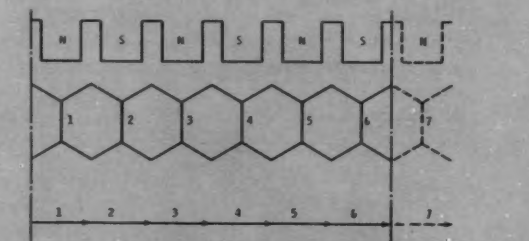
When the machine is operated as a 24-pole generator, the voltages generated in the coil groups are all in phase with each other, and may be added vectorially in a straight line, as shown in Figure 1, to obtain the total generated voltage.

However, for 28-pole operation the pole pitch of the stator winding differs from the rotor pole pitch. Figure 2 shows that there are seven groups of stator coils occupying the same physical space as six field coils. As a result of this difference, the voltages generated in the individual coil sides are not in phase with each other, and must be added vectorially, as shown, to obtain the total generated voltage.

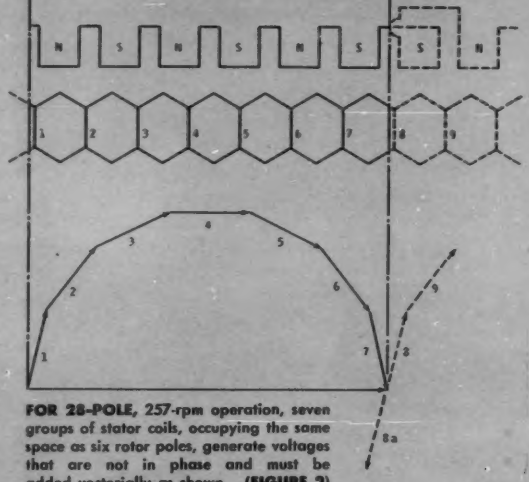
Since the first group of six rotor poles covers a span of seven stator coil groups, the first and eighth coil group voltages are 180 degrees out of phase. Consequently, the polarity of the next group of six rotor poles must be reversed in order to obtain proper operation. Without this reversal of rotor pole polarity, the voltages induced in the second group of seven stator coil groups would be 180 degrees out of phase with those of the first group, and the total voltage generated will become zero. For example, the voltage generated in coil sides numbered 1 and 8 in Figure 2 are in phase with each other and are equal in value. Without the polarity reversal of the second group of field poles, the voltage generated in coil side 8 would be displaced 180 electrical degrees, as shown by vector 8a, and would be equal and opposite to the voltage of coil side 1, so that the two would add vectorially to zero.

Thus, by reversal of polarity of the proper rotor pole groups and the use of a second stator winding, operation at a second synchronous speed may be obtained. However, not all speed combinations are feasible.

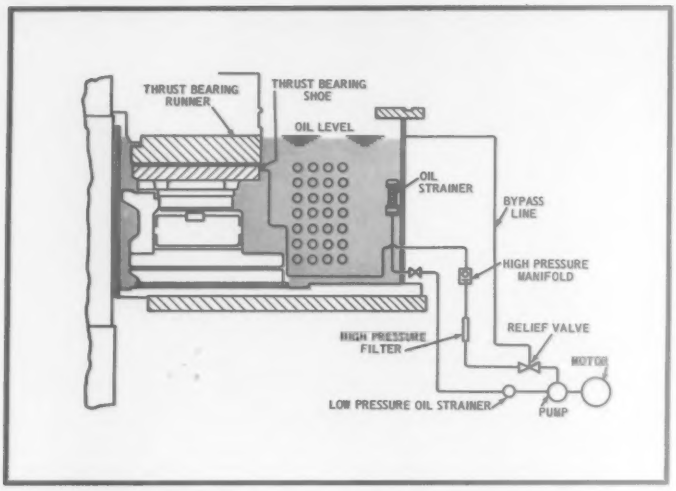
Obviously, for 28-pole operation the machine's magnetic circuit is not used efficiently. Therefore, to produce a given kva with this arrangement requires a machine larger in physical size than normal. The stator must carry two independent windings, one for each speed. Since the cost of a two-speed synchronous motor-generator is about 85 percent greater than the cost of a normal machine built for the lower of the two speeds, careful study of the proposed



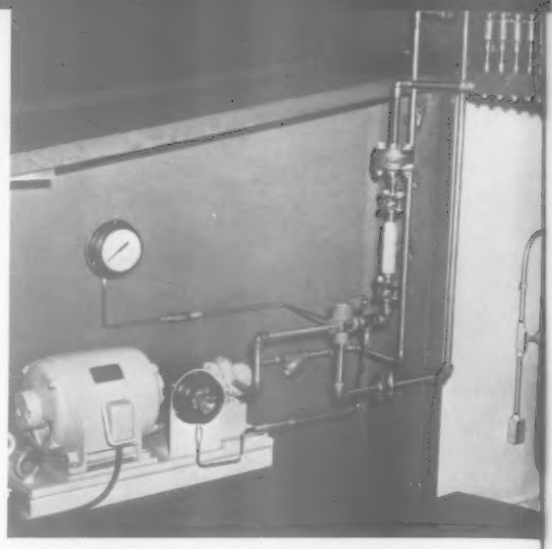
FOR 24-POLE, 300-rpm operation, the two-speed machine operates as an ordinary 24-pole unit. Voltages generated in stator coil groups are in phase and added in a straight-line vector. **(FIG. 1)**



FOR 28-POLE, 257-rpm operation, seven groups of stator coils, occupying the same space as six rotor poles, generate voltages that are not in phase and must be added vectorially as shown. **(FIGURE 2)**



STARTING FRICTION is reduced by forcing high pressure oil between the thrust bearing runner and shoes. Lubrication oil occupies the reservoir space around the bearing indicated with color. **(FIGURE 3)**



HIGH PRESSURE oil pump, its driving motor, relief valve, filter, and other parts external to the bearing housing, indicated schematically in Figure 3, are shown. **(FIG. 4)**

installation must be made to determine if two-speed operation can be economically justified.

In some cases a different rated voltage may be desirable for motor operation than for generator operation. Such is the case for the Hiwassee unit being built for Tennessee Valley Authority, which will be rated 13,500 volts as a motor and 13,800 volts as a generator. This requirement is usually the result of locating the unit near the end of a transmission line where the large motor load encountered during the pumping cycle may result in a voltage drop.

In two-speed units, each of the two stator windings can be designed for the desired voltage. In a single-speed machine, which utilizes the same winding for both motor and generator operation, the design is based on a compromise voltage to obtain proper operation at either voltage.

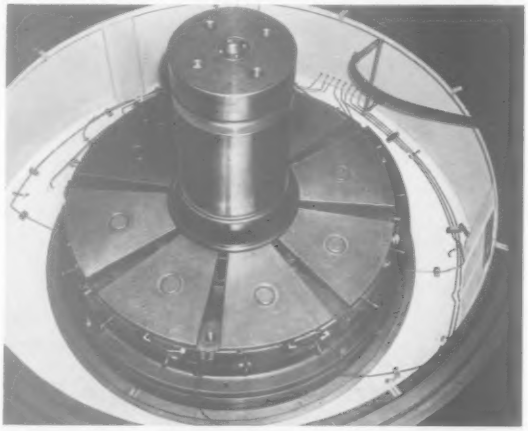
Load and voltage are reduced to ease starting

When operating as a motor for the pumping cycle, the machine must be capable of bringing the pump up to speed. Usually reduced-voltage starting, commonly used with smaller motors, is the most satisfactory method of starting the unit. The proper starting voltage is normally obtained from taps or possibly from a tertiary winding on the main transformer bank.

In order to reduce the starting kva, the pump is unwatered. This is accomplished by closing the pump discharge valve and introducing compressed air into the pump to depress the water to a point below the runner. Thus the torque which the motor must develop during the starting period need be only sufficient to overcome the friction and windage of the unit, plus the torque required for acceleration of the unit's Wk^2. To further reduce line disturbance when starting, breakaway torque is reduced to practically zero by using a high pressure lubrication system to establish an oil film between the thrust bearing surfaces at standstill.

A schematic diagram of a high pressure oil system for this purpose is shown in Figure 3. Oil is taken from the bearing oil reservoir at a point near the normal oil level. The oil passes through two strainers in series before entering the suction side of the high pressure oil pump. The pump delivers oil at a pressure exceeding 1000 psig, in an amount approximately double the amount required to maintain sufficient oil film thickness in the particular bearing. A pressure relief device, together with a bypass line, is provided to bypass the oil not required by the bearing. The parts of this high pressure system external to the bearing housing are shown in Figure 4.

After leaving the pump, the oil passes through a high pressure filter to remove any sediment from the oil before it reaches the bearing shoes, then enters a manifold which is external to the bearing housing. Separate high pressure oil lines extend from this manifold to each bearing shoe. The oil then passes through internal passages in each shoe to an outlet near the center of the shoe's babbitted surface, as shown in Figure 5.. A circular groove in the babbitt assists in distribution of the oil over the shoe surface.



CIRCULAR GROOVES near the center of each thrust bearing shoe distribute the lubricating oil under high pressure. **(FIGURE 5)**

This high pressure system is now being installed on all pumped-storage units and on other hydroelectric generators where operating requirements make it desirable. Experience with installations already made shows that, with the high pressure system in operation, breakaway torque is reduced to a value low enough so that one man can start a large unit rotating by pushing against one of the rotor spider arms.

Generators for hydroelectric plants are usually equipped with amortisseur or damper windings, which are noncontinuous between poles. In order to develop the starting torques required for a pumped-storage application, this winding must be continuous between poles, and special attention must be given to supporting the connections between poles against centrifugal stresses at overspeed. The amortisseur winding may also need high thermal capacity in order to absorb the heat generated in it during the starting period.

Pumped-storage units may also be started for the pumping cycle by other methods when local conditions permit their use. For example, if the pumped-storage machine is located in a power plant containing other normal hydraulic generator units, it may be started by tying it electrically to a generating unit with both machines at standstill, and bringing the two up to speed in synchronism. This requires a separate source of excitation for both machines, since field current must be applied to both units at standstill, at which time direct-connected exciters are inoperative.

This same method can be used to start a pumped-storage unit when using a generating unit located at a remote point, provided a transmission line that can be isolated from the system during starting periods is available. After the unit is up to speed, it can be synchronized with the system and operated in a normal manner.

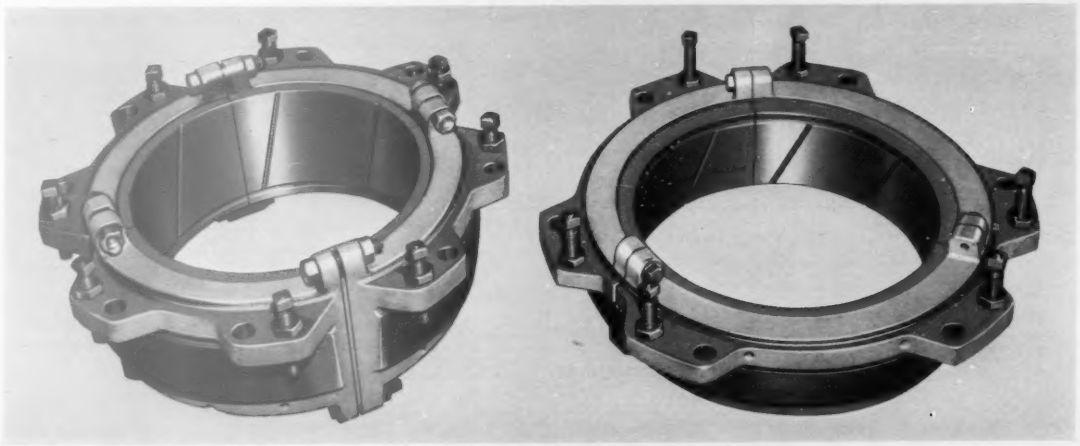
Modifications are required for reversible rotation

A reversible pumped-storage unit must operate in either direction of rotation — one direction for pumping and the other for generating. Reversal of rotation is accomplished electrically by reversing the line connections to two terminals by means of a double-throw disconnect switch or by means of two separate interlocked circuit breakers.

Certain mechanical modifications are necessary to permit such operation. For example, axial-flow type rotor fans cannot be used for machine ventilation. Instead, a radial-bladed centrifugal-type fan is used to give effective machine ventilation regardless of the direction in which the machine is rotating.

The Kingsbury-type thrust bearing is inherently suitable for operation in either direction of rotation and requires no special consideration. The guide bearing or bearings must, however, be modified by the addition of a second set of oil grooves. Guide bearings for vertical machines are self-lubricated by grooves in the babbitt which slope upward in the direction of rotation, as shown in Figure 6. The rubbing of the shaft against the oil trapped in these grooves produces a viscosity pump action which effectively circulates the oil through the bearing. For a reversible unit each guide bearing must be provided with an additional set of oil grooves of opposite inclination. This provides proper oil circulation in either direction of rotation.

The principal differences between a generator-motor for reversible pumped-storage use and a normal hydro-generator include the addition of a motor rating, the requirements for synchronous motor starting, and modifications for reversible operation. A number of minor considerations also arise. For example, the polarity of the main and pilot exciters reverse with a change in the direction of rotation, and zero center meters are required for the excitation circuits. On the other hand, the characteristics of a reversible pump-turbine, as compared to a normal hydraulic turbine, sometimes simplify the design problems of the electrical unit. The overspeed of such a unit is somewhat lower than for the usual hydraulic turbine, permitting a greater latitude in electrical design. Since pumped-storage units will seldom be used for system regulation, normal values of flywheel effect are usually satisfactory.



GUIDE BEARINGS are self-lubricated by viscosity pump action as the rotating shaft carries oil up grooves in the babbitt. For reversible generator-motors, two sets of grooves having opposite inclination are required. **(FIGURE 6)**

PUMP-TURBINES

(Continued from page 17)

During periods when the reservoir is full and pumping is not required, the unit can be operated for best efficiency as a turbine by adjusting the wicket gates to conserve water. In some cases where the storage reservoir is very large, such as at Hiwassee, the pump-turbine can be operated like a conventional Francis turbine. If there are no wicket gates, a butterfly valve is provided and used for starting and synchronizing, then opened wide for generation or pumping, and closed for shutting down.

A conventional Francis turbine does not make a good reversible pump-turbine. The runner, designed for generating power, does not make a good pump impeller. An impeller-runner for a reversible pump-turbine is usually larger in diameter than a Francis runner, and the buckets are designed to give high efficiency for flow in either direction. A Francis turbine would have to be run at much higher speed for pumping against the head used for generating power. Unstable flow when pumping would cause noise, and possible vibration and damage to the runner. In addition, a Francis turbine would have to be submerged much deeper below tailwater than a reversible pump-turbine in order to avoid cavitation.

Starting and stopping the unit as a pump

A reversible pump-turbine, like a centrifugal pump, must have its runner at least partly submerged in the water in order to avoid priming. When starting as a pump, the wicket gates are closed, the motor is started and the unit brought up to normal speed. When full pressure is built up against the closed wicket gates, they are slowly opened to proper gate opening (usually 80 to 90 percent gate) and water flows up the penstock into the storage reservoir. The wicket gates remain in this position until, with rising head, flow diminishes and a new gate position is necessary to maintain maximum efficiency. If the pumping period lasts 9 or 10 hours and the change in head is very gradual, the gates may need to be adjusted only two or three times. At the end of the pumping cycle the wicket gates are slowly closed to zero gate opening before the motor is disconnected from the line.

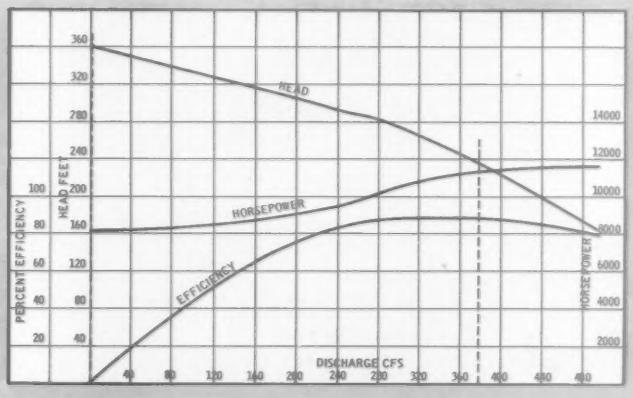
Generally speaking, reversible pump-turbines will be large, rated 10,000 horsepower or more. Since the shutoff power required to drive the pump with closed wicket gates may be great enough to cause system disturbances — it varies between 40 and 90 percent of rated power, depending upon the specific speed of the pump — a method of reducing these disturbances was developed. With the wicket gates closed, compressed air at about 100 psi is admitted through a pipe on the cover plate, forcing the water out of the runner, reducing shutoff power to approximately 3 to 5 percent of full-load power, thus minimizing any disturbance when the motor is disconnected from the line.

A similar method is used to reduce current inrush when placing the pump load on the line. Just before starting the pump, the wicket gates are closed and compressed air is admitted in the same manner. Initial blowdown of the water is accomplished at 100 psi, and this pressure is maintained until the water level drops to 2 or 3 feet below the bottom of the runner. Then a float switch, connected to the side of the draft tube, cuts off the main supply of compressed air, and a smaller auxiliary valve opens as the water level begins to creep upward. This smaller valve bleeds in just enough air to maintain the water level in the draft tube within a range of about 2 feet.

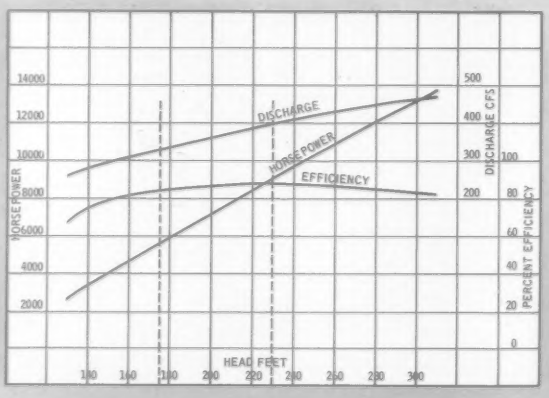
After the water is blown down, the unit is started with the impeller-runner rotating in air. In this manner, starting load is reduced and any disturbance to the system is insignificant. When the unit is up to speed, air is expelled through the connection on the cover plate, permitting the water to rise and fill the runner. After all the air is expelled, the wicket gates are opened and the unit starts pumping.

As a turbine

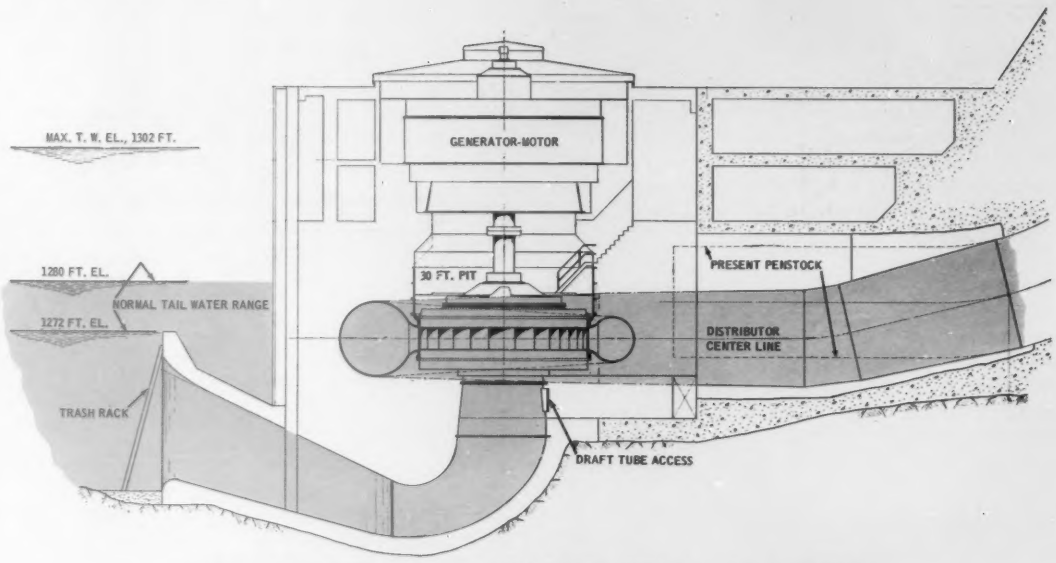
When starting a reversible pump-turbine as a turbine, the wicket gates are opened a small amount, and the unit is brought to normal speed without any load. It is synchronized to the line before the circuit breaker is closed. Then the wicket gates are adjusted to carry the load assigned to the unit. Shutting down is the reverse — the wicket gates are closed slowly, and when the unit reaches speed no load the circuit breaker is opened to remove the unit from the line. Then the wicket gates are closed to zero gate, and after the unit slows down, brakes bring it to a stop.



PRELIMINARY POWERHOUSE tests of the Flatiron unit used as a pump were confined to range between dotted lines and conformed closely to model test curves shown adjusted to full scale. **(FIG. 3)**



AS A TURBINE, powerhouse tests to date have been confined to a narrow range indicated between dotted lines. Close conformity to model tests indicates guarantees will be exceeded. **(FIGURE 4)**



RATED TO GENERATE 80,000 hp under 190-foot head at 105.9 rpm and to pump 3900 cfs against 205-foot head at the same speed, the Hiwassee unit will use wicket gates. **(FIGURE 5)**

If there is an electrical failure which disconnects the generator-motor from the system when operating as a turbine, the unit may overspeed and can go up to full runaway speed. However, runaway speed for a reversible pump-turbine is generally less in proportion to normal speed than for a Francis turbine, and the pump-turbine and generator-motor are built to operate safely at maximum overspeed. Of course, the wicket gates will be arranged to close in such an event, and the overspeed will be of short duration.

Synchronizing can be done with a butterfly valve

If there are no wicket gates, a butterfly valve is used to start up the pump-turbine. When starting as a pump, the butterfly valve is closed. Compressed air at 100 psi can be used to blow the water out of the spiral case and runner in the same manner as with wicket gates. After the pump is up to speed, the air is expelled and pressure built up against the closed butterfly valve. When all of the air is expelled, the valve is opened slowly to its full open position and water is pumped up the penstock. When shutting down the unit, the butterfly valve is closed and the unit is taken off the line.

For starting as a turbine, the butterfly valve is opened a small amount (10 to 30 percent). The unit gradually comes up to speed, and the valve opening is limited to an amount that will hold the speed of the unit just below normal. Then a small bypass valve is opened and the speed creeps up to normal. This can be closely regulated and synchronizing with the line is very smooth. After synchronizing, the circuit breaker is closed. When shutting down the unit, the butterfly valve is closed slowly, and when the generated output comes down to zero the circuit breaker is opened. This is speed no-load position on the butterfly valve, and the valve continues to its full-closed position.

The butterfly valve is always wide open when the unit is pumping or generating. It is not used to regulate flow because the valve gate or wicket causes disturbance in the flow of water when in a partly open position. Noise results and cavitation takes place. If allowed to continue for a long time, damage to the valve housing and wicket from pitting may result. Of course, in normal operation the time for synchronizing is very short, 3 to 5 minutes, and not long enough to cause any significant damage.

Submerged setting is necessary

A pump-turbine must have its impeller-runner full of water or, with the vertical type generally used, the lower part of the runner buckets must be submerged in order to start pumping. The distance that it has to be submerged below tailwater depends upon the head and discharge at the start of the pumping cycle.

In order to maintain proper flow through the impeller-runner when pumping, there must be sufficient pressure head at the bottom, or eye diameter. This head is sometimes called the Net Positive Suction Head, NPSH. It is expressed in feet of head above zero on an absolute scale. The NPSH is expressed by the following formula:

$$\text{NPSH} = H_b - hvap \pm hs$$

where H_b = atmospheric pressure in feet of water — 33.9 feet at sea level (about 1 foot less for each 1000 feet of altitude above sea level).

$hvap$ = pressure at which water vaporizes at the temperature of the water (about 1 foot for 75 F).

hs = distance in feet from tailwater to bottom of runner buckets (+ if tailwater is above and — if tailwater is below the buckets).

The ratio of the NPSH to the total head is called sigma.

This ratio becomes critical when cavitation starts in the impeller-runner. Cavitation will cause a disturbance in the flow, which may in turn cause a breakdown in the head, accompanied by a loss in efficiency when pumping. In turbine operation, cavitation may cause a breakdown in the horsepower developed, also accompanied by a loss of effi-

ciency. Therefore, the sigma used for each application must be greater than the critical sigma. Generally speaking, high head pump-turbines will require lower sigmas (.05 to .10), while low head units require higher sigmas (.30 and up). The sigma for proper submergence must be figured for the lowest pumping head, usually occurring at the start of a pumping cycle.

A pump-turbine would not be set with its horizontal centerline above tailwater, because this would require external priming by pumps or ejectors to raise the water into the impeller-runner. During the pumping cycle the tailwater can be drawn down a limited amount, because as the head goes up the discharge is reduced and the critical sigma is lowered. If the centerline of the pump is submerged sufficiently to satisfy the critical sigma for pumping, it will be adequately located to prevent cavitation during turbine operation.

Two-speed operation

Sometimes it is possible to obtain better performance by operating the pump-turbine at a lower speed for turbine operation than for pumping. The pump-turbine now installed in the Flatiron Power and Pumping Plant of the Bureau of Reclamation in Colorado is of this type. It operates at 300 rpm when pumping and at 257 rpm when generating power. It has a synchronous 60-cycle generator-motor that was especially designed for this application. By running at the lower speed as a turbine, the unit develops higher overall efficiency and develops more horsepower at the lower heads. In this application the head varies from 290 feet to 140 feet for the turbine, and 170 feet to 300 feet for the pump. When head range is as large as this, runner characteristics may be such that more power and higher efficiencies are obtained by running the turbine at a lower speed than the pump. Of course, the generator-motor is more expensive to build for two-speed operation, and the gain in horsepower and efficiency must be enough to justify the additional cost. Additional switching equipment is also required when two-speed operation is used. At the higher heads (500 to 1000 feet), the head range will probably not be enough to make two speeds economical, while for heads below 150 feet the characteristics of the runner are such that there is not sufficient gain in performance to justify the additional cost.

Size of units and head limits

Reversible pump-turbines can be built in sizes as large as are practical for Francis turbines. They can be built to develop 150,000 hp and more in a single machine, if a suitable generator-motor can be matched to their speed and power. The larger impeller-runners can be cast in sections and assembled at the powerhouse by bolting the sections together. The impeller-runner for the Hiwassee pump-turbine will be made in three sections, because it is more than 22 feet in diameter.

Reversible pump-turbines can be furnished for the same range of head that is practical for Francis turbines. They can be used under heads as low as 50 feet, or as high as 1200 feet. Low specific speed reversible pump-turbines are used for heads 200 feet up to 1100 feet, and high specific speed units for heads below 200 feet. They are single-stage machines, and the selection must consider how much excavation will be required for the proper submergence; also whether a suitable speed can be obtained to match the speed of a synchronous generator-motor.

Pump-turbines prove themselves in use

Reversible pump-turbines will generally develop higher efficiency when pumping than when operating as a turbine. For example, efficiencies as high as 92 percent can be expected for the larger units in the medium specific speed range when pumping, while the corresponding turbine efficiency may be 1 to 5 percent lower, depending upon the specific speed of the unit and whether it is operated for maximum efficiency or for maximum kilowatts delivered to the switchboard.

Three identical reversible pump-turbines have been built for use in Brazil, two for the Pedreira Pumping Station and the third for the Edgard de Souza Plant. These units are rated 19,000 hp under 89 feet head as turbines, 1800 cfs against 78 feet head as pumps. The speed is 150 rpm. The first unit has been in operation for over a year and has given fine performance.

A two-speed reversible pump-turbine built for the Bureau of Reclamation has been installed at the Flatiron Power and Pumping Plant near Loveland, Colorado. This is a completely new development and is the first two-speed unit in the world. Water is pumped from the tailrace of the powerhouse through a penstock and tunnel about 7500 feet long into Carter Lake, where it is stored for irrigation. The surplus water, not required for irrigation, is returned through the unit to develop power. This unit will generate more than 12,000 hp under 290 feet head, and will run at 257 rpm. It will pump 370 cubic feet of water per second against a head of 240 feet, and will run at 300 rpm for pumping. Preliminary results of powerhouse tests conform closely to the model tests and indicate that all guarantees will be exceeded by ample margins.

Of course, each application must be studied and judged upon its own merits, but there are a great many installations where pump-turbines will be found to be economical and will be a sound investment.

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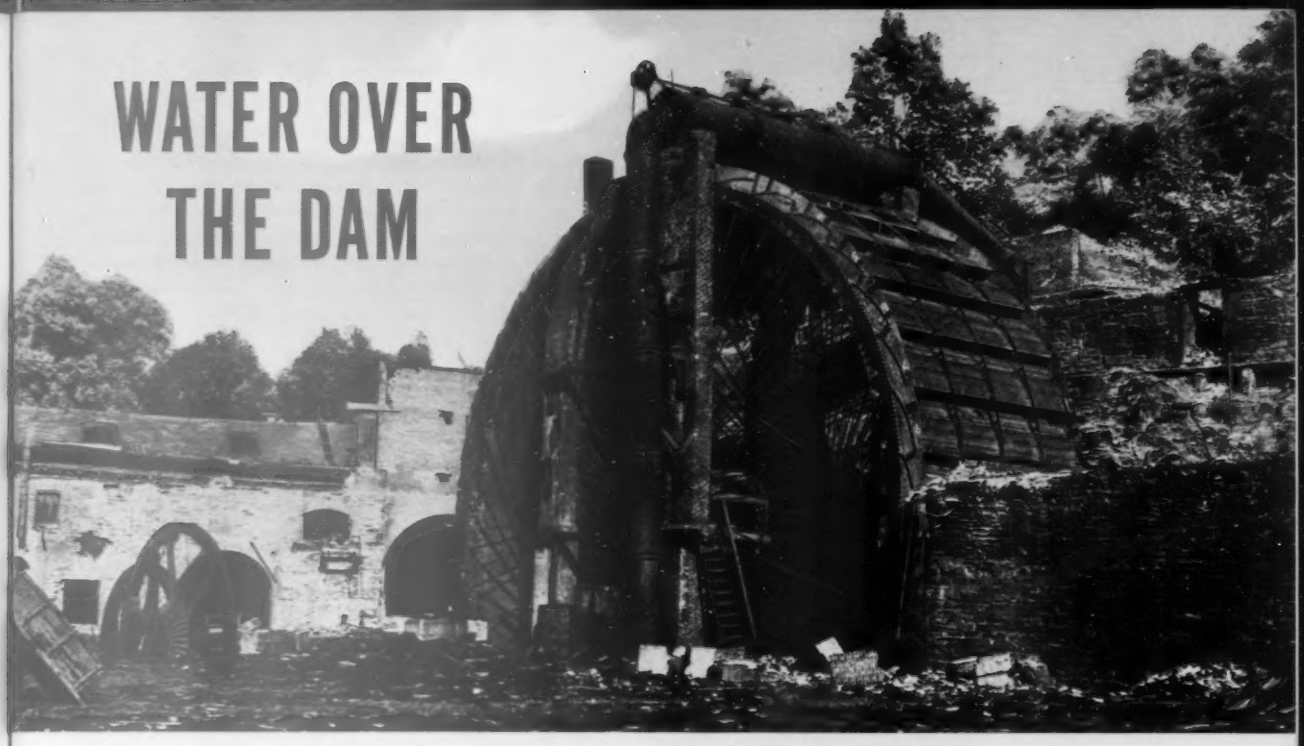
WATER OVER THE DAM



AMERICA'S LARGEST overshot water wheel, built by Burden at Troy, New York, in 1851 was 60 feet in diameter and powered machines mass producing spikes and horseshoes.* **(FIGURE 1)**

PART 2

by **EDWARD UEHLING**
Hydraulics Section .
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OUR EASTERN STATES, with the Appalachian Mountains and their Piedmont areas passing through, were especially fortunate in having had abundant, easily developed water power sites. These were used to great advantage, not only in New England and Virginia, but in New York State, New Jersey, and Pennsylvania. Long Island, New York, had many old mills,[12] and large numbers of overshot wheels were scattered throughout the Catskill Mountains.

Washington in 1790 paid a historic visit to Roslyn, Long Island, New York (called Hempstead Harbor prior to 1844). His diary for April 24th of that year mentions his visit with Heinrich Onderdonk, operator of a grist mill and two paper mills. Evidence in the possession of Jesse Merritt, Nassau County historian, places the building of the older Onderdonk paper mill as 1733 or earlier. According to Morton Pennypacker, Suffolk County historian, there is no doubt that New York State's first paper mill was established in Roslyn. By the 1890's even Roslyn's second paper mill was discontinued, and the water wheel had already been replaced by steam power.[13]

The first paper mill in America[14] was erected on Wissahicken Creek at Germantown, near Philadelphia, in 1690. The needs of a Philadelphia printer, William Bradford, and the ambitious German paper maker William Rittenhouse made this mill and partnership prosper.

Ruins in the northwest part of New Jersey bear silent witness to the old Oxford furnace of more than 200 years ago. It stood "beside a raceway that carried water from Furnace Creek to turn the water wheel that ran the stamping mill, as well as the big leather bellows that blew air into the furnace." "It was built in 1742 by Jonathan Robeson, in what was then the wilds of Morris (now Warren) County, and for 140 years served New Jersey well."[15]

After the Revolutionary War, the trail of the pioneer led into western Pennsylvania, Kentucky, Ohio and the Northwest Territory. With him came the ubiquitous grist mill, saw mill, and his desire to establish new industries, which again prospered because of water power. Although the iron industry had crossed the Susquehanna River westward as early as 1760, "the first furnace west of the Alleghenies was built in 1790 on a little stream that became known as Jacob's Creek, an affluent of the Youghiogheny."[16] "All of the early forges used water power, producing charcoal iron. Coal, which was to revolutionize the industry, came into use on the eve of the Civil War."[17]

The demand for overshot wheels about this time caused Samuel Fitz to start the manufacture of "Overshoot Water Wheels" in the year 1840 at Hanover, Pennsylvania. The company he established, through the years has built this type of wheel — primarily of wood at first; later, of all-steel construction and quite efficient design. Wheels of 30 and 40 feet in diameter are still in operation. A 1928 Fitz water wheel catalog states: "These wheels have brought prosperity to water power mills throughout the country for they afford steady power and constant service from streams that would be worthless with any other type of wheel. There are more than 750 mills and factories in the State of Virginia alone." Fifteen hundred overshot wheels are estimated to be in operation today (1954).

* Photo courtesy Greater Troy Chamber of Commerce.

Burden overshot holds American size record

The demand for Henry Burden's[18] machine-made spikes became so great that on two occasions he increased his water power capacity on Wynantskill, which enters the Hudson at Troy, New York. First, in 1838-39 he replaced five separate water wheels with one very large one. "In 1851 the old wheel was replaced by the present one, which is hereafter described. Standing upon one of the galleries winding about its huge frame, the visitor beholds this mighty wheel majestically doing the work of twelve hundred horses. It is an overshot wheel, sixty feet in diameter, and with a width of twenty-two feet. Around its broad periphery are thirty-six buckets, six feet three inches deep. Six hollow cast-iron tubes form the axis of this great wheel, which are keyed into flanges, seven feet in diameter, and from each flange diverge iron rods two inches thick, 264 in number, which terminate at the circumference of the wheel. The water, which sets in motion this remarkable wheel, flows from a reservoir-dam, about 1200 feet distant, through a canal to the distributing reservoir, having a head of eighteen feet above the wheel."[19]

It was the duty of the wheelman to regulate the water supply so that the wheel, shown in Figure 1, would turn at constant speed of 2½ rpm, as required. The annular segmental rack drove 7-foot diameter pinions, the latter being keyed to shafts extending some 31 feet into the factory.[20] "Looking upon the trains of rolls, the rotary squeezers, the furnace blowers, the horseshoe rivet and punching machines, and the other appliances in motion for manufacturing iron, one sees more appreciably the immense power furnished by this huge wheel constructed by the mastermind of Henry Burden."[19] Abandoned about 1897, it nevertheless remained intact for some fifteen years longer.

In comparison, the famous Laxey overshot wheel, built in 1854, on the Isle of Man, England, had a 72-foot 6-inch diameter, but only a 6-foot width. It developed about 230 hp to pump water from a 1250-foot deep mine abandoned in 1929. The wheel remains as a tourist attraction.[21]

Rice's old mill, illustrated in Part I, some 30 miles north of Knoxville, dates back to the time John Adams was President. About 1790, a group of families from the western Carolinas settled in the fertile Clinch River valley. Here, in 1798, James Rice, by his own skill and knowledge of machinery, built this grist mill with its overshot wheel. The mill was always kept in good repair and operation from generation to generation until 1935, when Norris Dam was constructed. At that time, it was systematically dismantled by the National Park Service and carefully rebuilt in another nearby location.

Originally the shaft was poplar, but around 1900 was replaced by one made from a huge oak log. The cog wheels were made of choicest hickory. By 1893 a more modern grinding process had been installed to produce bolted flour. People within a radius of 15 to 20 miles brought their wheat and corn to Rice's mill for grinding. Over the years, various attachments had been devised so that the old mill, in addition to grinding grain, could saw lumber, gin cotton, and operate grinding and other tools, including a trip hammer. About 1899, a small dynamo attachment was constructed for generating electric power for lighting the mill and Rufus Rice's home. These lights were a topic of wide conversation, for electric light had been almost unheard of in that section of Tennessee.[22]

In the old pioneer days the water wheel driven mill was not only an economic necessity but served as a social center, which ranked second only to the church. The early settler would sling a bag of grain across the back of his horse or, if living at greater distance, might haul his grist or logs by ox team. Since "going to mill" was one of the few occasions when busy neighbors could chat together and exchange ideas, such trips came to be regarded as pleasure rather than a burdensome chore.

In more level areas of the Middle West, good water power sites were not always plentiful for these essential grist mills. At Whitewater, Wisconsin, for example, the only practical mill location in the 1830's was owned by a man without capital to build one. Community pressure compelled him to either build, sell, or be run off his claim. A doctor bought his claim for $500 and a mill was built.[23]

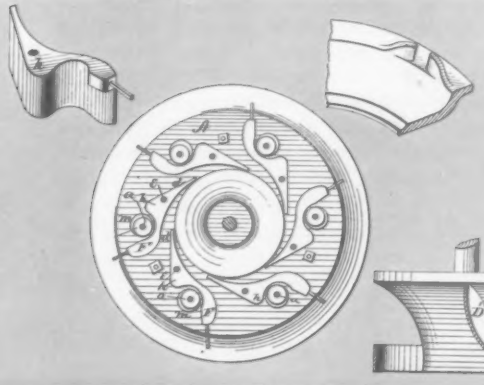
Water wheels spread out with the pioneer

The first settlement in Indiana was established at the Falls of the Ohio in 1784,[14] opposite the present city of Louisville, Kentucky. Lumber and grist mills at St. Anthony Falls (Minneapolis), Minnesota, were built as early as 1822.[14] Streams throughout the Middle West were being spotted for small mills.

"By 1849 Milwaukee, Wisconsin, had four water power flouring mills and one steam mill."[24] In that city, one factory† especially grew rapidly, meeting the early demands for water wheel driven saw and milling machinery. "By 1873 its millstone department had roughly 50 men devoted to nothing but dressing French burr millstones."[25]

In 1877, a turbine invented and built by Stephen Morgan Smith, shown in Figure 2, was the start, at York, Pennsylvania, of yet another water wheel business. The

† E. P. Allis Company.



PATENT DRAWINGS, dated September 1879, show unique gate features of Stephen M. Smith's turbine. **(FIGURE 2)**

McCORMICK WHEELS, built by several manufacturers, were among the widely used early turbines. **(FIG. 3)**

original 18-inch turbine was installed and operated for years at Jacob's grist mill on Beaver Creek. With the trade name *Success*, improved turbines of this make appeared, being supplemented in 1889 by the acquisition of manufacturing rights for the McCormick turbine,[26] of which varieties were also built by others like Jolly, Hunt, and Wellman-Seaver-Morgan. One is shown in Figure 3.

First hydroelectric central station built

"Most authorities agree that the first hydroelectric central station in the United States, if not the first in the world, was in a small shed-like building at Appleton, Wisconsin,"[27] shown in Figure 4, placed in operation September 30, 1882 — just 26 days after the first operation of Edison's famous Pearl Street steam-electric central station in New York City. H. J. Rogers, a leading businessman, who had organized the Appleton Edison Electric Company, thus lighted his own new residence and two paper mill buildings. The service was from "dusk to dawn."

The station had a small vertical turbine wheel, built by Morgan and Bassett, under patents of a Mr. Elmer of Berlin, Wisconsin. The wheel was 3½ feet in diameter and operated at a speed of 72 rpm under 10-foot head. Big bevel gears drove a horizontal jack shaft having a big pulley belted across to a line shaft. A second pulley on the line shaft was then belted back to a horizontal Edison dc dynamo, which produced enough current to supply 250 16-candlepower lights (about 12½ kw).[28]

The August 21, 1886, issue of the old *Electrical World* stated that "at the present time, there have been between 40 and 50 American and Canadian electric light plants depending largely—many . . . wholly—upon water power."

Most notable in the East were Rochester, Niagara, Holyoke, West Somerville, Massachusetts; Laconia, New Hampshire; and Skowhegan, Maine. In Canada, there were Dunnville, Galt, Napanee, Ottawa, Pembroke, Port Hope, and Peterborough. The largest plants in the South were at Lynchburg, Virginia, and Columbus, Georgia.

In the Middle West those cited were at Dayton, Ohio; South Bend, Indiana; and at Aurora, Elgin, Sterling, and Ottawa, Illinois; Alpena and Grand Rapids, Michigan; Crookston and Minneapolis, Minnesota; and Beatrice, Nebraska. In Wisconsin there were Appleton, Eau Claire, Wausau, and Janesville. The Far West had Aspen, Colorado; Ogden City, Utah; and Spokane Falls, Washington.

Rushmore[29] states that by 1896 (just 10 years later) there were nearly 300 hydroelectric plants in operation.

Water power speeds industrial growth

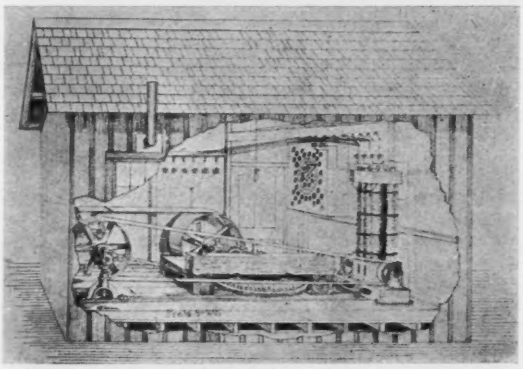
Rochester, New York, is selected as representative of many American cities made large and prosperous by plentiful adjacent water power, which, in these early days, was almost the only reason for their coming into existence. Here the total fall of the Genesee River was about 257 feet, divided into several cataracts. Ebenezer Allen built a saw mill and a grist mill as early as 1789.[14] Water wheel driven flour mills followed and flourished during the years wheat was still abundantly grown in that area. Later, many other industries derived mechanical power from the Genesee River.

As already noted, Rochester was one of the early cities to convert part of its water power into electricity. The April 14, 1888, and August 10, 1889, issues of *Electrical World* call attention to a hydroelectric plant at the foot of Lower Genesee Falls, under 94-foot head, which included 15 twin 15-inch "Lesser" turbines of 300 hp each. The power was used for "about 1200 arc lights, some 200 motors, and over 1000 incandescent lamps." The August 24, 1889, issue tells of the J. G. Davis & Co. having put in a single horizontal cylindrical casing 90-foot head *Victor* turbine, with grooved pulley for rope transmission, to drive a 500-barrel flour mill, a 50-light dynamo and a freight elevator — throwing in and out the latter being "scarcely perceptible."

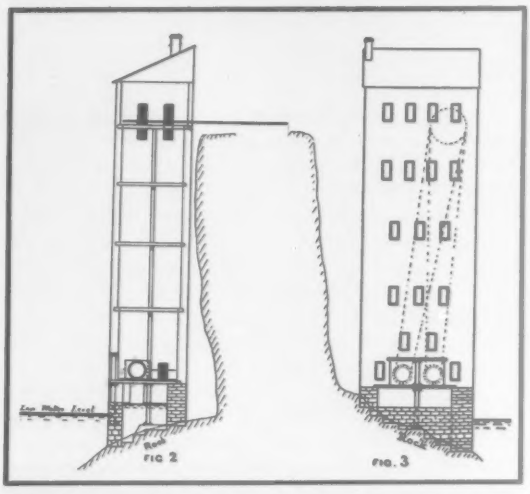
In this age of individual motor drives for each machine in our modern factories, it is difficult to visualize mills all cluttered by a maze of pulleys, ropes, belts, gears, and long line shafts. Nevertheless, all transfer of early water power from wheel to driven machine was entirely mechanical. As larger and larger water wheels or turbines were required to drive a series of flour mills, textile mills, or other machines, this mechanical transmission became quite complicated. Pulleys on one or more jack shafts drove line shafts on other floors, or even into adjacent buildings where the power was used. For several decades, even after the advent of the hydroelectric unit, mechanical drives were still common practice.

In November 1891, for example, a brand new power plant, shown in Figure 5, was put into operation at the foot of Rochester's Genesee Falls. It consisted of two separate twin horizontal turbines, each of 600 hp under 87-foot effective head. A 5-foot rope pulley on each turbine shaft transmitted the power to an elevation 90 feet above the turbine floor. Here a 12-foot rope pulley on a horizontal main shaft transmitted the power into the upper factory level, for further distribution. The rope speed, said to be one of the highest, was 7540 feet per minute.[30]

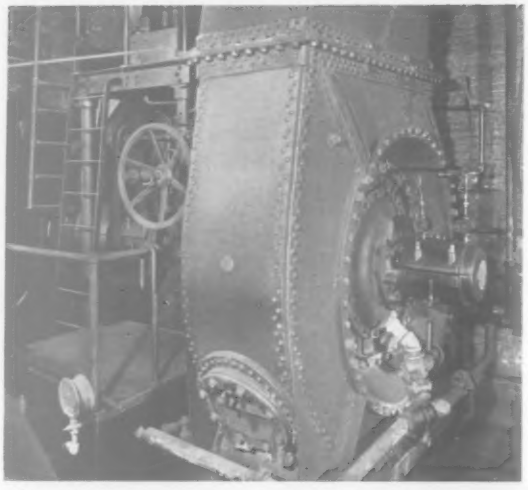
"As late as 1890, eight years after Appleton, experts from many parts of the world who were studying the Niagara Falls power potentialities still recommended the transmission of mechanical power by rope drive, water pressure and compressed air . . . there was much skepticism about going to the relatively unproven medium of elec-



AMERICA'S FIRST HYDROELECTRIC central station is shown in cutaway to expose equipment installed in generator room. **(FIGURE 4)**



LONG ROPE transmissions to line shafts were common practice in the 1890's. This Rochester plant was built in 1891. **(FIGURE 5)**



INSTALLED IN 1904 at Rochester, N.Y., this 1250-hp, 88-foot head, 50-year-old turbine is still in operating condition. **(FIGURE 6)**

tricity. The promoters of Niagara were even led to offer a monetary prize for a workable solution to this problem of transmission. It is interesting . . . that both Lord Kelvin and Thomas Edison recommended direct current transmission, while George Westinghouse seems to have been alone among the experts recommending alternating current.[27]

About 1725, and some 47 years after Father Louis Hennepin first saw the Falls, the first water wheel driven saw mill was constructed along the Niagara River by the French to furnish lumber for Fort Niagara.[31] Not until the 1860's and 70's was water, brought around to the 215-foot high bluff, utilized in modest quantities under an assortment of heads up to 90 feet. Only after the Schoellkopf interests took over in 1877, and the canal had been enlarged, was there real evidence of power development.

The proprietary interests of the canal produced and transmitted *mechanical* power to adjacent buildings of their main factory clients. A little of this, furnished in 1881 to the Brush Electric Company, was in turn utilized to drive a generator producing enough current for 16 arc lights. This installation has been precluded from consideration as a central station because the water power and electric power were not produced on the same premises or by the same company.[27]

The year 1895 was outstanding at Niagara, marking the record installation of the first ten 5000-hp hydroelectric units built for the Niagara Falls Power Company at Station 1. They were of the double-runner Fourneyron type, built by the I. P. Morris Company from designs of Faesch and Piccard, of Geneva, Switzerland, for a head of 135 feet. Clemens Herschel,* as consultant for the first big Niagara developments, was convinced that Swiss hydraulic turbine designs were superior to American ones of that early day. Slightly earlier, the largest capacity hydroelectric units in America with reaction-type turbines were one 2000-hp and two 1000-hp Globe Iron Works units installed in 1893 at Niagara, Ontario, under 65-foot head.[27]

In 1896 at Station 2, Leffel came in with 1650 and 1900-hp units under 212-foot head. These, together with some by I. P. Morris, provided a total of fifteen more units.

* First manager (1904) Allis-Chalmers Hydraulic Dept., inventor of the Venturi meter.

In 1902, for the same station, eleven more 5000-hp, 135-foot head units were built by I. P. Morris from designs of Escher-Wyss, of Zurich, Switzerland.

At that time the 200-foot high bluff below the American Falls resembled a huge dyke which had sprung large leaks at many elevations, each leak representing one or more of these early Niagara water power installations.

In 1901 the E. P. Allis Company worked out a merger which united it with several other well-known industrial firms* to form Allis-Chalmers. This new company recognized that water power development in America was on the threshold of a new era, involving much larger capacity hydroelectric units under much more difficult operating conditions.† It therefore engaged Clemens Herschel to work out an arrangement to utilize designs and technical help from the Swiss,** and in 1904 entered the hydraulic turbine business. The first turbine built and installed that year, shown in Figure 6, is still in operating condition (1954). Rated 1250 hp at 360 rpm under 88-foot head, it was constructed for Station 4 of the Rochester Railway and Light Company.

Impulse wheel originated in the Far West

The discovery of gold by James Marshall while building a water-powered lumber mill for John A. Sutter near Coloma, California, in 1848, caused a tremendous westward migration, both by land and sea, of people seeking their fortunes through mining. Mining required power machinery, and steam-driven equipment was too bulky and costly to trek across the wilderness of a continent. A new type of water wheel solved the problem, and made the Far West flourish.

We are greatly indebted to an engineer, named W. A. Doble, who 55 years ago prepared a long treatise on "The Tangential Water Wheel."[32] These wheels were "essentially a California development, in that their perfection was brought about through the natural conditions imposed

* Included were Fraser-Chalmers and Gates Iron Works, both of Chicago.

† Bullock Electric Co., builders of generators, became a part of this company in 1904.

** Modified Escher-Wyss practice soon developed into new independent design for American requirements.

in the mining regions of the Golden State, where limited quantities of water at high heads constituted practically the only form of water power available for working the mines and mills." For most of his information on the earliest tangential wheels, Doble gratefully credits the first-hand knowledge of Samuel N. Knight, of Sutter Creek.

"The miners of California had independently developed the 'hurdy-gurdy' wheel, which, though crude, was the immediate forerunner of the modern type of tangential wheel. The original hurdy-gurdy wheel (named after the musical instrument) resembled a circular saw with straight cut teeth more than anything else; the principal difference being that the hurdy-gurdy was made of wood, varying in thickness up to 2 or 3 inches or more." See Figure 7. "The teeth or buckets were then closed by casings (shrouding) of wood which formed the sides of the wheel."

"The water was applied at first in the form of a jet, emanating from a hole bored in the end of a wooden block with which the pipe had been plugged . . . with heads varying from 40 to 50 feet; square wooden pipes were frequently used. These were merely square wooden boxes, bolted together with iron rods, if such could be secured, otherwise . . . clamped together." "The jet was applied exactly as in present forms of tangential wheels."[32]

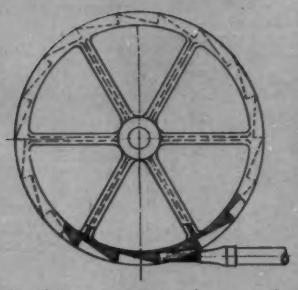
The Far West, however, was rapidly developing. The first transcontinental railroad to San Francisco was completed in 1869. In no other region were systems of fluming, ditching, and piping so well developed. The growing mining industry demanded more water power under still higher heads.

One marked improvement in the old hurdy-gurdy was due to the aforementioned S. N. Knight, who brought out an elongated cup-shaped bucket, shown in Figure 9, in his wheel of 1870. Placer mining methods had brought into being some excellent nozzles, and wooden wheels were being equipped with iron buckets as soon as available.

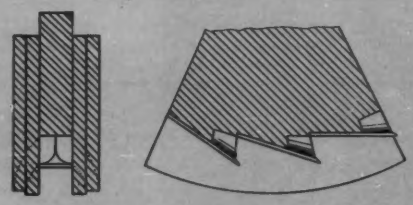
Lester Pelton had come to California in 1850 by ox team from Ohio at the age of 21, to seek an elusive fortune in the Far West. Until 1864 he was engaged in mining without too much success, and also did millwrighting at Comptonville until 1878. During this time he made a large number of tests trying to improve the hurdy-gurdy. He first placed curved buckets alternately. He then combined his buckets, with a splitter in the center, with astonishing results. The splitting wedge did away with the dead water that accumulated in cup-shaped buckets. He took immediate steps toward a patent, which was obtained in October 1880. His patent drawing is shown in Figure 10. This major improvement was the real beginning of the modern impulse wheel as used today, and which is still often referred to as the Pelton-type wheel.

Improvements on impulse wheel continue

Other minds had been working simultaneously on improving the hurdy-gurdy wheel. Doble called the origin of the jet-splitting wedge a "vexed question." Knight is his authority that a Nicholas J. Colman, of Railroad Flat, California, had somewhat the same idea in 1873 — his patent drawing is shown in Figure 8 — but had never built wheels. Among other claimants were Joseph Moore

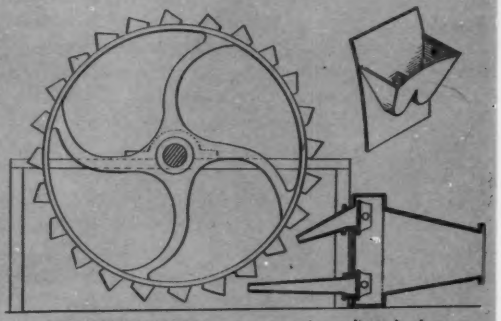


EARLIEST of western tangential water wheels, the hurdy-gurdy was developed in California. **(FIG. 7)**



PLOW-SHAPED buckets characterize the patent drawings of N. J. Colman, dated Feb. 18, 1873. **(FIG. 8)**

ELONGATED CUP-SHAPED buckets appear in S. N. Knight's January 1875 patent drawings. **(FIGURE 9)**



THE LESTER PELTON patent covering splitter buckets was obtained in October 1880. **(FIGURE 10)**

A DIVIDING RIDGE and staggered buckets were used on the Cascade impulse wheel of 1891. **(FIGURE 11)**

THIS PUMPING ENGINE, built for the City of Niagara Falls in the 1890's, was driven by an impulse wheel. **(FIGURE 12)**

of San Francisco and Professor Hesse of the University of California. Doble states: "While it is cheerfully conceded that Mr. Pelton may have made his invention without cognizance of the work previously done by either Mr. Moore or Professor Hesse, the fact remains that his work was several years later than theirs." He did believe, however, that Pelton was entitled to the credit he claimed.

Even by the end of the 19th century, many improvements had been contributed by large numbers of people and companies. Among the latter were the Abner Doble Company, the Risdon Iron Works of San Francisco, and the Pelton Water Wheel Company. Advancements involved better shapes and curves for the faces of the buckets, new methods of fastening buckets, and ways of controlling single and multiple jets. Even predating Doble's writing, in 1899, the impulse wheel had already permitted "a very wide and free scope to the designer, wheels having been made in California from 3 inches to 30 feet in diameter, and to work under heads from 35 to 2100 feet under speeds ranging from 65 to 1150 rpm . . . a number of single wheels having a capacity of not less than 1000 hp each." He concluded, "that the development of open or impulse wheels, like all other mechanical implements, had to pass through a period of evolution, and the results obtained are the cumulative work of many men."

How the above two basic improvements in the hurdy-gurdy affected its efficiency is told by W. E. Wines in a May 26, 1897, article[33] concerning earlier model tests conducted at the University of California using a ⅜-inch jet under 50-foot head. Efficiencies obtained were 40.4 percent with just flat buckets, 65.6 percent using plain curved buckets, and 82.5 percent using curved buckets with a wedge or splitter. Elsewhere he mentions 85 percent efficiency with Pelton-type wheels as having been reached.

Wines also mentions the Leffel *Cascade* turbine patented in 1891, and pictured in Figure 11, which he described as having "two separate sets of buckets located alternately on opposite sides of a continuous dividing ridge."

Impulse wheels provide great adaptability

The impulse-type wheel, by its simplicity and versatile speed possibilities, readily made direct drives possible in most cases, when powering hoists, stamping mills, air compressors, pumps, and other mining machinery. Thus in the Far West, as well as in Alaska, the cumbersome gear trains and belted drives so commonly used with water wheels and turbines in the Eastern States were generally unnecessary because of the impulse wheel. A large mine hoist built in 1894, for example, had a double Pelton-wheel drive.[34] One set of buckets and jets drove the drum in one direction when lowering, another set provided opposite rotation when lifting.

A Riedler[34] air compressor, designed and built in 1893 for the Alaska-Treadwell Gold Mining Company, was driven by a Pelton wheel, direct connected to the crank shaft. The wheel, formed by the heavy 20-foot flywheel to which the Pelton buckets were bolted, operated at 78 rpm under 460-foot head.

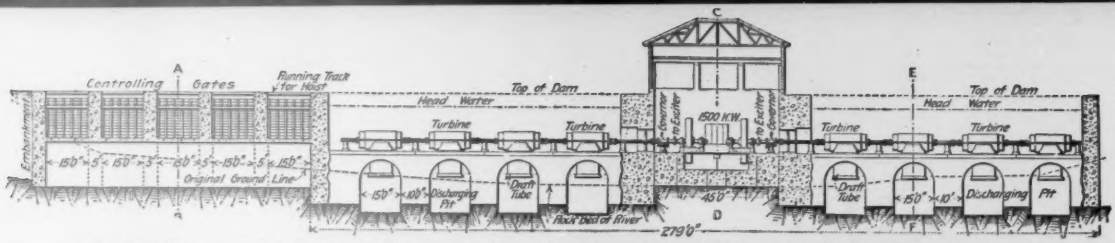
The compressor took 2800 cubic feet of free air per minute, and compressed it to 80 psi. The water at this plant being insufficient to drive the wheel during a dry period of two months out of the year, auxiliary Corliss engine steam cylinders were situated in tandem behind the air cylinders. A testimonial letter dated July 31, 1894, eight months after installation, said the compressor was "giving excellent results, and every satisfaction, while running either by steam, or by water power."

Not quite so well known is the fact that two large impulse-type turbines, built by the Pelton Company, were put into operation in the 1890's by the City of Niagara Falls pumping plant. Each was applied to a six million gallon per day Riedler duplex pumping engine.[34] The wheels and pumps were located in a subterranean chamber in solid rock, 130 feet below the Niagara River, the tailrace discharging through a tunnel below the Falls. The impulse buckets were again bolted to the 12-foot diameter, 12,000-pound flywheel, operating under 125-foot head at 76 rpm. Each wheel had two nozzles, one used for normal pressure and both together for fire service. See Figure 12.

Water wheel brings prosperity to Far West

Water wheel installations in California were astonishingly large in number. No one knows how many hurdy-gurdies or their early replacements were in operation during those days. A 1909 Pelton water wheel catalog, however, listed 8554 wheels of this make alone just in California, Oregon, and Nevada, aggregating 836,000 hp. Another 762, aggregating 76,000 hp, were mentioned as being in Washington, Idaho, and Alaska, 485 more in Hawaii, Utah, Colorado, Montana, New Mexico, and Arizona, only 183 in the Middle West and Atlantic Coast States. Of these ten thousand wheels, by 1909, 431 were electric power installations, aggregating nearly 455,000 hp.

The 50 light Brush arc dynamo driven by a 70-foot head Pelton wheel, installed in 1885 at Aspen, Colorado, apparently was the first hydroelectric unit in the Far West.[27] In 1892 electric power for the first long distance transmission line in the United States (45 miles at 10,000 volts)[29] was produced by 440-foot head Pelton wheels, driving single-phase generators at the San Antonio Light and Power Company plant at Pomona, California.[35] The Mill Creek plant at Redlands, California, with two 250-kw generators driven by Tulson wheels put in operation in 1892 under 295-foot head, is reputed to be the first three-phase hydro installation.[27]



EACH OF TWO tandem units having eight *Samson* wheels was direct connected to a 1500-kw generator at Lowell Dam, Kansas.

Just as there were a few Pelton-type units in the East, so there were also some Francis-type units in the Far West. "The first alternating current hydroelectric station in the United States was the Oregon City or Station A plant of the Willamette Falls Electric Company, later the Portland General Electric Company."[27] The single-phase belted generators went into operation in 1889, driven by *Victor* turbines. *Electrical World,* September 13, 1890, issue, mentions a 2700-hp hydraulic installation at Spokane Falls, Washington, in 12 twin horizontal units under 70-foot head. These, also built by Stillwell-Bierce, consisted of four pairs of 15-inch and eight pairs of 10-inch wheels.

Five vertical *New American* turbines of 195 hp each, under 14-foot head, were installed at the Spokane, Washington, pumping station in the 1890's.[36] These units, shown in Figure 14, were respectively geared to four horizontal duplex Holly pumps and to one generator. Francis-type hydroelectric units included such installations as the 1897 rope-driven, 1300-hp, 28-foot head unit at Sacramento, California, the three 5000-hp, 125-foot head 1906 direct-connected units at Portland, Oregon, and the three 600-hp, 18-foot head 1907 Dayton Globe wheels at Billings, Montana.[27]

Current wheels were quite extensively used in southern Texas, Mexico, and California, and in Colorado prior to 1893.[37] Small boxes or vessels attached to the outside of the revolving paddle wheel carried up small quantities of water that emptied near the top into a spout or flume for irrigation. The latter part of the 19th century found many variations of these also in Idaho, Utah, and Washington. Some described in a long 1904 article[38] display considerable local ingenuity.

Age of modern hydroelectric power dawns

The February 5, 1887, issue of *Electrical World* mentions a "magnificent water power" at Lockport, New York, used to produce electric power for the Cowles Electric Smelting and Aluminum Company. Here, on 18 Mile Creek, a number of 550-hp, 240-rpm, 35-foot head twin horizontal *Victor* wheels, by leather belt drives, transmitted their power to Brush *Colossus* dynamos on the floor above.

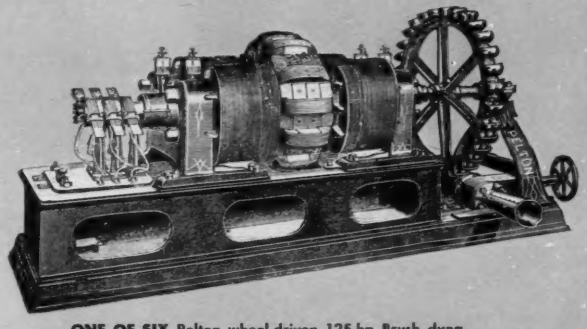
About 1890, in the depths of one of its mines, probably the first subterranean hydroelectric station, the Chollar Mining and Milling Company, in Nevada, installed six 125-hp hydroelectric units in two parallel rows. These 900-rpm direct-connected horizontal generators were driven by single-jet, 40-inch diameter, phosphor bronze Pelton wheels, see Figure 13, under 1680-foot head, the electric power being used in nearby operations.[39]

The Columbia (South Carolina) Cotton Mills is reported[40] as being the second cotton mill in America to be driven by electricity. The turbines consisted of two twin Stillwell-Bierce 48-inch *Victor* wheels coupled together and connected to a 700-hp generator (no head mentioned).

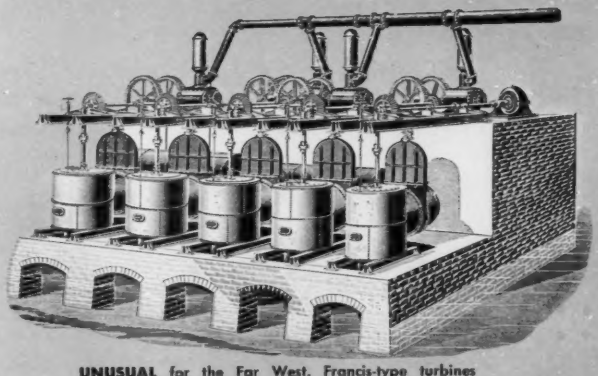
By 1900 the St. Lawrence Power Company at Massena had a good start on its 150,000-hp project under about 45-foot head. This development consisted of 5000-hp sextaplex (triple twin) horizontal *Victor* units connected to correspondingly rated generators. About that time, it was written: "The St. Lawrence Power Company has acquired about 2000 acres of ground suitable for manufacturing purposes, and it is expected to sell power to companies which will locate near the plant on account of the low cost of available power."[41]

Around the turn of the century, adequate designs of thrust bearings, so important to large capacity higher head vertical Francis units, were still in the future. Likewise, high speed Francis units, and especially propeller-type units for low head developments, were still several decades away.

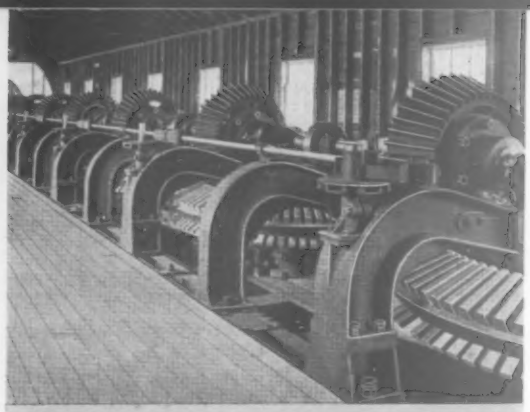
One standard practice was to build horizontal units in which two runners, one left-hand and one right-hand, were placed on the shaft as a twin pair, so that their hydraulic thrusts tended to neutralize each other. In low head developments, in order to produce higher speeds for larger capacity generators, two or more such sets of twin runners, mounted on their shafts, were coupled together to form one hydraulic turbine unit.



ONE OF SIX Pelton wheel-driven 125-hp Brush dynamos installed about 1890 is shown. **(FIGURE 13)**



UNUSUAL for the Far West, Francis-type turbines were installed at Spokane in the 1890's. **(FIGURE 14)**



EIGHT VERTICAL WHEELS transmitted power to a horizontal generator through these gears at Otsego, Michigan. **(FIG. 15)**

Original units installed at Kilbourn plant[42] on the Wisconsin River, for example, consisted of four 6-runner (triple twin) horizontal shaft 2000-hp Wellman-Seaver-Morgan turbines and two twin 250-hp Jolly-McCormick turbines under 17-foot head.

At Lowell Dam in eastern Kansas — just west of Joplin, Missouri — there were in successful operation two hydroelectric units, each of which had four pairs of twin *Samson* runners (eight runners per unit). Each complete unit, rated about 2800 hp at 180 rpm under 24-foot head, was direct connected to a 1500-kw horizontal generator. See illustration at the top of page 33.

In many other low head plants, to keep the individual thrusts low and to suit higher generator speeds, two or more vertical turbines were often hooked together on one cross horizontal shaft by means of gear harness, the single horizontal shaft being coupled to one generator. The Otsego, Michigan, plant of the old Kalamazoo Valley Electric Company, see Figure 15, had eight 56-inch vertical wheels connected in this manner.

Early editor caught vision of the future

"The electrical transmission of power over long distances is a demonstrated success. This fact gives an immediate value to water powers, which have hitherto remained unimproved . . . our country abounds in such water powers, some of immense magnitude, and it is only a question of time when all will be improved and the power generated, transported by wires to the surrounding cities and towns, and utilized for light, heat, and power."[43]

Even this editor would have gasped if he could have foreseen the actual accomplishments of the last fifty years — 70,000-hp Francis turbines for Niagara,* 123,800-hp Kaplan propeller units for The Dalles project, 150,000-hp impulse wheels for the Kemano project. The United States alone, according to recent reports,[44] has 21.5 million kilowatts of hydroelectric power developed. And still there are an estimated 88 million more potential kilowatts of hydro power in our country waiting to be conquered — to conserve our resources . . . to bring additional prosperity to future generations.

* 150,000-hp units have been installed at Grand Coulee.

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THE KILBOURN PLANT, when put in operation in 1909, had four six-runner horizontal shaft 2000-hp units.

ALLIS-CHALMERS

Electrical REVIEW

EDITOR

Just as soon as it is ready, send me a copy of the booklet now being printed containing both parts of Mr. Uehling's article "Water Over the Dam."

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Editor

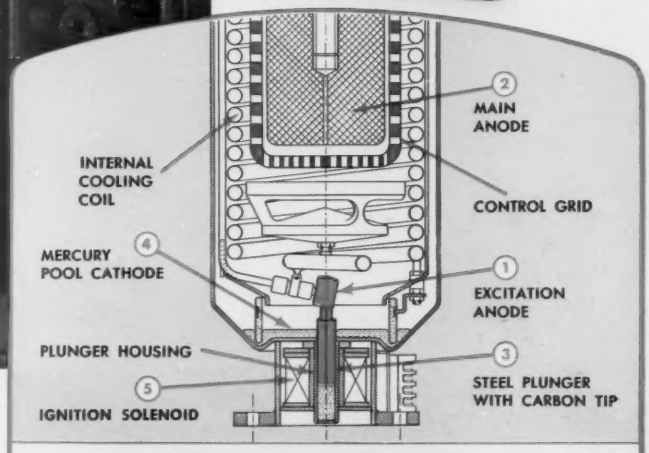
ELECTRICAL REVIEW
Allis-Chalmers Mfg. Co.
Milwaukee 1, Wis.

Here's the Rectifier That Needs

No Delicate Adjustments

THIS 1000-KW, 615-VOLT DC, six-tube excitron rectifier is installed in an automatic transportation substation.

ALLIS-CHALMERS
Mercury Arc Rectifiers



Unique Plunger Starts Continuous Excitation

The excitron tube has an excitation anode ① in addition to the main anode ② . With the excitation circuit de-energized, the steel plunger ③ floating in the mercury pool cathode ④ makes positive contact with the excitation anode (as shown).

When the excitation circuit is energized, the ignition solenoid ⑤ pulls the steel plunger ③ away from the excitation anode ① and under the mercury pool cathode ④ , thus drawing a dc arc and forming the cathode spot, which makes conduction of load current by the tube possible.

If power is interrupted the plunger will float up, contact the excitation anode and automatically re-establish the excitation arc when power is restored.

LITTLE MAINTENANCE IS NEEDED with Allis-Chalmers excitron-type rectifiers. Excitation of the excitron rectifier is continuous, while other types of rectifiers require re-ignition 60 times a second.

Since it is more difficult to start a rectifier arc than to maintain it, the excitron rectifier is much less likely to lose excitation during operation. Momentary dips in supply voltage which are encountered in many supply systems have no effect on the continuous excitation arc.

Years of operation in hundreds of installations have proved the reliability and ease of operation of Allis-Chalmers mercury arc rectifiers. You can get complete information from your nearby A-C office. Or write Allis-Chalmers, Milwaukee 1, Wis.

A-4432

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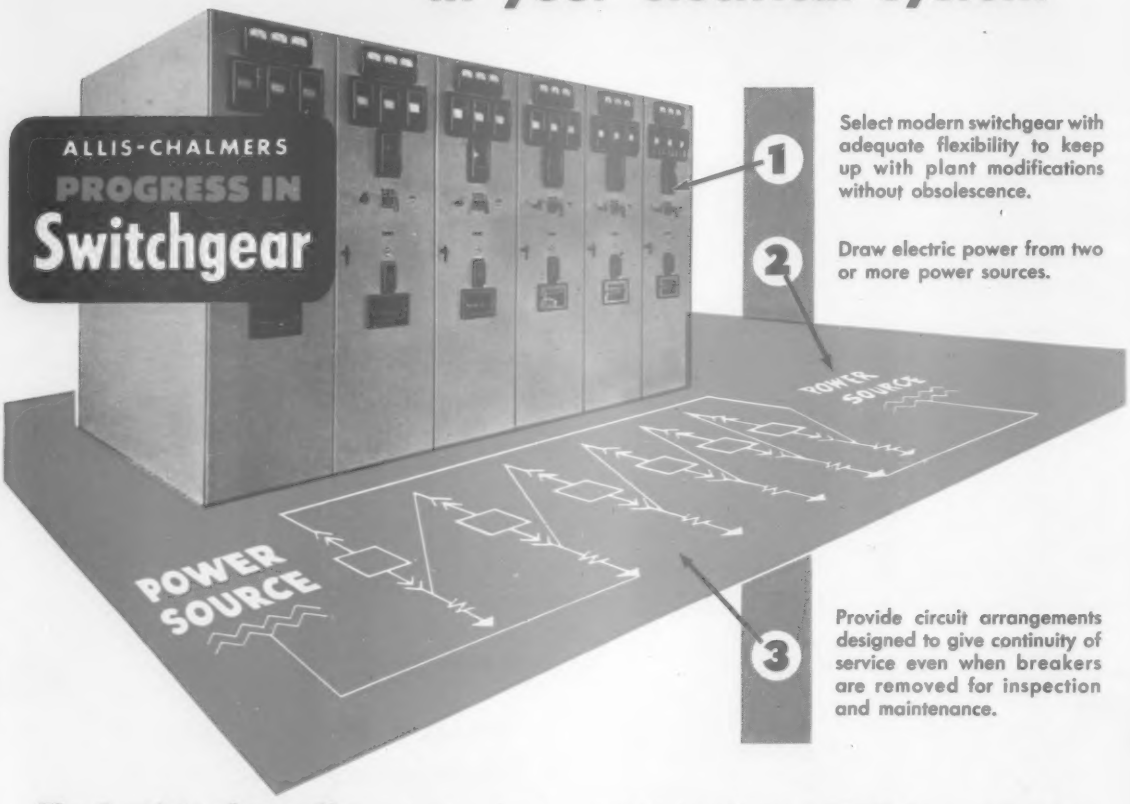
For uninterrupted power . . .

combine these 3 features

in your electrical system


ALLIS-CHALMERS
PROGRESS IN
Switchgear
POWER SOURCE
POWER SOURCE
1
2
3
Select modern switchgear with adequate flexibility to keep up with plant modifications without obsolescence.
Draw electric power from two or more power sources.
Provide circuit arrangements designed to give continuity of service even when breakers are removed for inspection and maintenance.

The 3 points above offer a simple rule of thumb for planning an electrical system that will provide uninterrupted power.

Key to the operation of such an electrical distribution setup is the switchgear. Allis-Chalmers has specialized in this type of switchgear engineering and offers these advantages to the user:

SAVES SPACE — Allis-Chalmers switchgear compartments are designed with room to permit adding special transfer bus or ring bus arrangements without adding auxiliary cubicles.

SAVES COST — No matter whether you eliminate duplicate facilities or simply eliminate extra cubicles, there is a substantial cost saving with Allis-Chalmers switchgear.

SAVES TIME — Allis-Chalmers dry-type bus joint insulation makes it easy to add or remove switchgear cubicles. No insulating compounds to melt . . . no fuss . . . no muss.

GET COMPLETE INFORMATION on Allis-Chalmers switchgear designed to meet needs for continuous power. Call your nearby Allis-Chalmers office, or write Allis-Chalmers, Milwaukee 1, Wisconsin.

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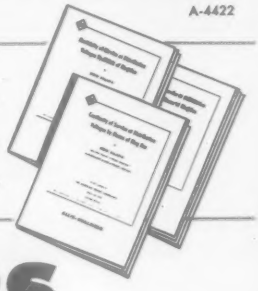
Ask for these booklets:

- ☐ Primary Switchgear Arrangement for Chemical Plants.
- ☐ Continuity of Service at Distribution Voltages by Means of Ring Bus.
- ☐ Design Considerations of Switchgear for Pipeline Substations.



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